

SOIL SCIENCE

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Contents for April, 1919

C. A. MOOERS. The Abnormality of Soils in Field-placed Cylinder Experiments.	247
C. E. MILLAR. The Comparative Rate of Formation of Soluble Material in Cropped and Virgin Soils as Measured by the Freezing-point Method.....	253
P. L. HIBBARD. Changes in Composition of the Soil and of the Water Extract of the Soil, Following Addition of Manure.....	259
ROBERT STEWART AND F. A. WYATT. The Comparative Value of Various Forms of Limestone.....	273
BURT L. HARTWELL, F. R. PEMBER AND L. P. HOWARD. Lime Requirements as Determined by the Plant and by the Chemist.....	279
FIRMAN E. BEAR AND ALBERT C. WORKMAN. The Ammonia-fixing Capacity of Calcium Sulfate.....	283
P. L. GAINNEY. Parallel Formation of Carbon Dioxide, Ammonia and Nitrate in Soil.....	293
WILLARD GARDNER. The Movement of Moisture in Soil by Capillarity.....	313
WILLARD GARDNER. Capillary Moisture-Holding Capacity.....	319

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THE ABNORMALITY OF SOILS IN FIELD-PLACED CYLINDER EXPERIMENTS

C. A. MOOERS

Agricultural Experiment Station, University of Tennessee

Received for publication March 17, 1919

In soil nitrogen studies (2) for the past 10 years at the Tennessee Agricultural Experiment Station, galvanized iron cylinders have been used to apparent advantage. The cylinder diameter was 2.225 feet, which gives a soil exposure of $\frac{1}{10,000}$ acre. Cylinders of both 4-foot and 1-foot depth were used and in both cases rested with open ends on undisturbed subsoil. The 4-foot cylinders were filled with subsoil and soil in layers as found in the field. For the 1-foot cylinders only surface soil was used. In these experiments no artificial watering was given, the idea at the outset being to allow the crops to grow under as nearly natural conditions as possible.

In the 4-foot cylinders—series A to G inclusive—two crops, wheat and millet, were grown each year for the first 5 years. For the following 3 years only cowpeas were grown. The 1-foot-cylinder experiments have run only 4 years. Japan clover was grown the first season and cowpeas each year for the following 3 years.

A striking feature of the results obtained from every one of the 5 soils used has been the rapid decrease in crop yield, resulting in the complete failure of the crops in the course of a few years except where lime was applied. At least three of these soils, Cookeville, Crossville and Farm, are known to be in immediate need of lime in order to produce either maximum crops of cowpeas or satisfactory crops of red clover. All three are loamy soils, but differ in color, texture, and fertility, only the last mentioned being considered as highly productive. The fourth, or "Gallatin" soil, is a brown loam of high natural fertility. The fifth, or "Jackson" soil, is a grey-colored silt loam, ordinarily considered of poor texture and structure, but well enough supplied with lime so that clover and even alfalfa were little benefited by liming in field experiments. However, as is usual for Tennessee soils, chemical analysis did not show the presence of an appreciable amount of carbonate of lime.

Although there were wide differences in natural fertility between the different soils, even the poorest, the Cookeville and Crossville, were not so poor but that harvestable crops would be expected for many years. The field production of the Farm soil has been under constant observation by the writer for the past 14 years and of the Jackson soil for the past 8 years, and

TABLE 1
Relationship between liming and continuity of crop production in 4-foot-cylinder experiments
 (Soils placed in 1908; first crop harvested in 1909)

SOIL	CYLINDER NUMBER	TREATMENT*	YEAR OF FIRST CROP FAILURE	FIRST CROP TO FAIL	REMARKS—WEIGHTS OF AIR-DRY GRAIN AND STRAW
Cookeville...	A4	O	1912	Millet	1912 wheat crop 3.21 gm.
	A2	F	1914	Wheat	1913 millet crop 1.21 gm.
	A1	L			1914 wheat crop 39.03 gm.
	A3	LF			1914 wheat crop 62.69 gm.
	A7	PK	1912	Millet	1912 wheat crop 23.24 gm.
	A9	PKN	1912	Millet	1912 wheat crop 38.67 gm.
	A10	LPKN			1914 wheat crop 94.74 gm.
Crossville....	C4	O	1911	Wheat	1910 millet crop 14.15 gm.
	C2	F	1913	Wheat	1913 millet crop 1.04 gm.
	C1	L			1914 wheat crop 11.83 gm.
	C3	LF			1914 wheat crop 60.63 gm.
	C7	PK	1911	Wheat	1912 millet crop 0.36 gm.
	C9	PKN	1911	Wheat	1912 millet crop 28.97 gm.
	C10	LPKN			1914 wheat crop 50.84 gm.
Gallatin.....	E4	O	1913	Millet	1914 wheat crop 12.75 gm.
	E2	F	1914	Millet	Failure of millet in part due to season. 1914 wheat crop 163.10 gm. Cowpea crop failed in 1915 and thereafter.
	E1	L			1914 wheat crop 133.27 gm.
	E3	LF	1914	Millet	Failure of millet due to season. 1914 wheat crop 171.68 gm.
	E7	PK	1914	Millet	Practically no millet in 1913. 1914 wheat crop 4.77 gm. Cowpea crops failed in 1915, 1916 and 1917.
	E9	PKN	1914	Millet	1913 millet crop 0.63 gm. 1914 wheat crop 174.50 gm. Small cowpea crops harvested in all three years.
	E10	LPKN			1914 wheat crop 234.18 gm.
	G4	O	1917	Cowpeas	1914 wheat crop 74.21 gm.
	G2	F			1914 wheat crop 89.37 gm.
	G1	L			1914 wheat crop 96.41 gm.
Jackson.....	G3	LF			1914 wheat crop 89.07 gm.
	G7	PK			1914 wheat crop 65.28 gm.
	G9	PKN			1914 wheat crop 167.60 gm.
	G10	LPKN			1914 wheat crop 170.47 gm.

* The symbols of the third column are interpreted as follows:

F 6 tons of farmyard manure per acre applied in 1908 and again in 1911.

L 2 tons of ground limestone per acre applied in 1908.

P 300 pounds per acre of 16 per cent acid phosphate applied annually until 1915.

K 100 pounds per acre of muriate of potash applied annually until 1915.

N 160 pounds per acre of nitrate of soda applied annually until 1915.

both continue to be productive without the addition of either manure or lime, although the former responds readily to both materials and the latter to manure.

The accompanying tables give the essential data relating to these experiments. In the case of the 4-foot cylinders the results show that without lime the Crossville soil ceased to produce either wheat or millet after 2 years. Similarly, production ceased in 3 years for the Cookeville soil, and 4 years for the Gallatin soil, but continued for about 8 years for the Jackson soil. As a rule when production once ceased all future seedings resulted in failure. Particular attention is called to the fact that annual applications of soluble phosphate, potash and nitrogen did not extend the cropping period and that light applications of manure delayed crop failure only a couple of years for the Cookeville and Crossville soils.

TABLE 2
Yields of air-dry cowpea hay from Farm soil in 1-foot cylinders
(Soil placed in 1913. All manure and lime treatments made in 1913)

CYLINDER NUMBER	TREATMENT PER ACRE	HAY YIELDS		
		1915	1916	1917
		gm.	gm.	gm.
1	Burnt lime, 2 tons.....	107.5	246.5	216.0
4	Ground limestone, 4 tons.....	78.5	214.0	165.8
6	None.....	89.8	150.0	0.0
12	Manure, 12 tons.....	122.0	278.0	1.3
7	Burnt lime, 2 tons; manure, 12 tons.....	182.8	285.0	261.0
10	Ground limestone, 4 tons; manure, 12 tons.....	208.5	284.5	211.5
18	Manure, 30 tons.....	309.3	299.5	134.5
13	Burnt lime, 2 tons; manure, 30 tons.....	389.5	402.3	442.8
16	Ground limestone, 4 tons; manure, 30 tons.....	294.3	369.0	312.8
30	None.....	164.3	221.8	34.5

For the 1-foot-cylinder experiments, the yields of all the cowpea crops are given in table 2. The 1914 crop of Japan clover is omitted because the stands were very irregular so that there was no apparent relationship between the treatments and the crop production.

The results show that where no lime was applied the crops were practically failures at the end of 4 years. Even moderate to heavy applications of manure, as made at the outset, failed to do more than delay complete crop failure. On the other hand, the addition of either burnt lime or ground limestone enabled the production of excellent crops with no indication of immediate failure.

To account for the results, the writer sees only one unusual condition, the prevention of all run-off, that is, the projection of the cylinders for two or three inches above the surface of the ground forces the rainfall to stay in the cylinders so that an increased moisture supply, and at times excessive leaching, is the result. Apparently, therefore, the supply of bicarbonate of lime

was so greatly reduced under these conditions as to become the limiting factor and to bring about total crop failure in a very few years. Under field conditions, on the other hand, with less loss by leaching, crops continue to be produced, although for 4 of the 5 soils liming would be beneficial.

In view of these facts, the question may be raised as to the effect of the cylinder conditions on the availability of soil nitrogen, and, for that matter, on all the soil elements of plant-food, for soils of this character under similar climatic conditions.

In the absence of satisfactory comparisons of the losses of nitrogen under field and cylinder conditions, recourse can be had only to generalizations which are liable to more or less error. Perhaps they will serve to raise a question which should be settled by more definite evidence. The prevention of run-off—which has been estimated as high as 50 per cent of the total rainfall (1)—gives rise to several possibilities; one is, that a soil with but little granulation may become puddled, and a water-logged condition result. This occurred in the case of the Jackson soil where left uncropped. The presence, however, of a crop, even at an early stage of growth, always favored, to an appreciable extent, the passage of water through this soil. For example, a good stand of young wheat nearly always prevented water remaining on the surface to an injurious extent, even during periods of very heavy rainfall. On the other hand, on uncropped cylinders of this soil the water would stand for weeks, especially in the wintertime, if not removed by special means. Another possibility, of rather frequent occurrence, as a matter of fact, is that a sudden downpour of rain in the growing season may furnish little moisture to the crop in the field on account of the run-off, but in the cylinders all will be retained. These considerations lead to the conclusions that the increased moisture supply, at least for well granulated soils, would increase nitrate production, and that this, along with increased leaching, would result in a more rapid loss of nitrogen than would take place under field conditions.

With regard to the effect of the cylinder conditions on the availability of phosphorus and potassium, the writer can say only that those soils which were very poor in these elements failed to respond to the marked extent expected under field conditions.

In conclusion the writer will add that he wishes not to condemn cylinders, and other similar means of conducting experiments in the open, but only to call attention to certain defects and possible sources of error, which need to be overcome in order to make work of this kind comparable with field conditions, at least wherever the rainfall is at all heavy, and the soil of such a nature as to allow of any considerable run-off.

The writer has used covers with apparent good results in the case of a soil of poor granulation—one that was readily puddled—the covers being placed on the cylinders only at times of extra heavy rainfall. Also, the writer will suggest that the problem may be solved by having a vertical slot on one side of the cylinder so as to allow the escape of a certain excess of water, or even

permit of a continuous run-off. Since the soil height is variable, the opening should be adjustable and of easy control, and should be so arranged as to prevent the inflow of water from the outside.

SUMMARY

1. Five different kinds of soil when placed in cylinders sunk in the ground, and exposed otherwise to natural conditions, were found to become unproductive to the extent of complete crop failure in the course of from 3 to 8 years, except where limed. For none of the soils was such a result either observed or to be expected under usual field conditions such as are found in Tennessee.

2. Annual applications of acid phosphate, muriate of potash and nitrate of soda had little or no effect in preventing crop failure. Farmyard manure applied at the outset in moderate and even large amounts delayed crop failure only a year or two in most cases.

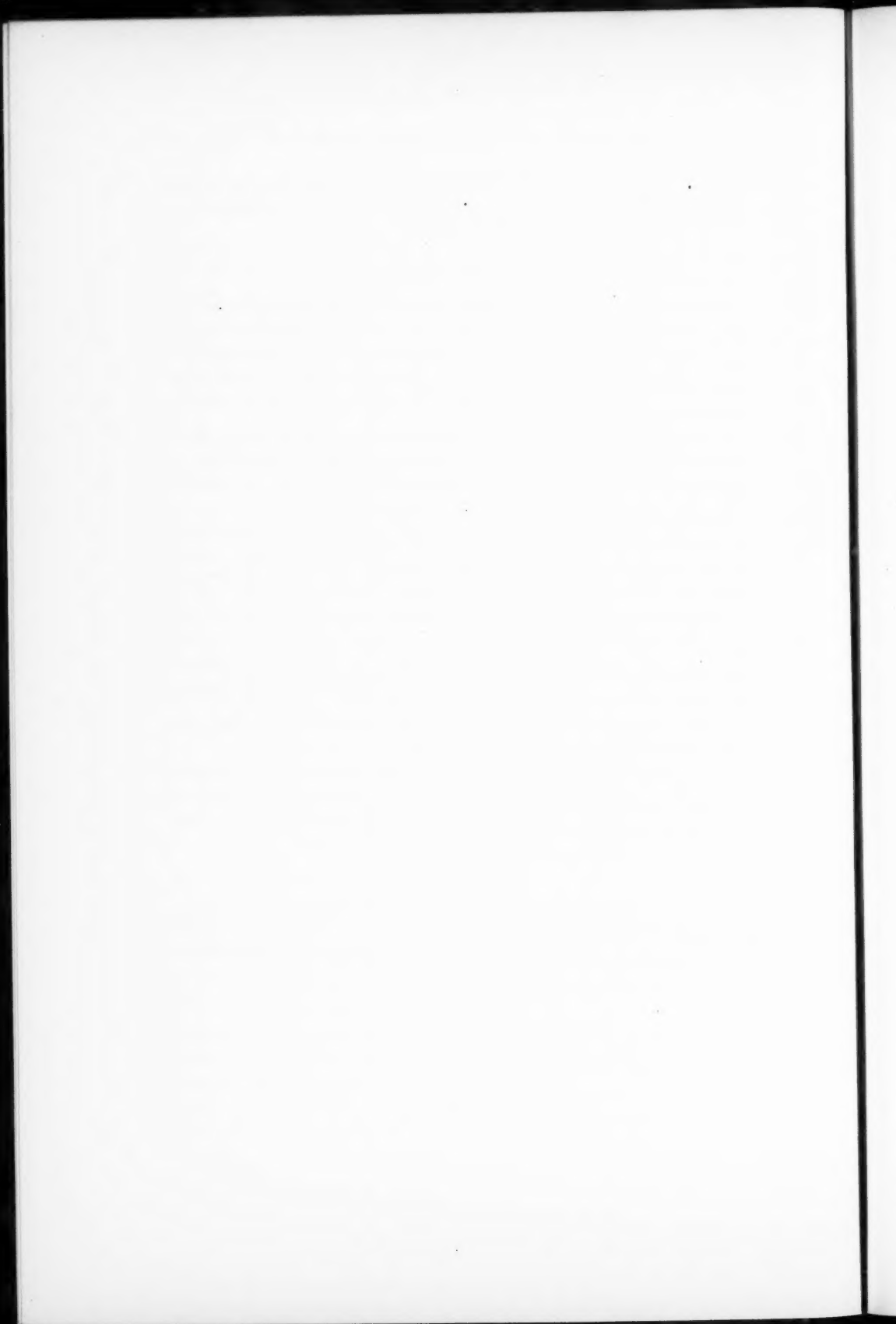
3. The only unusual condition apparent to the writer was the projection of the cylinder rims for 2 to 3 inches above the soil surface, thereby preventing all run-off of water in times of heavy rainfall. The increased moisture supply and the excessive leaching were assumed to reduced the natural soil supply of bicarbonate of lime until it became the limiting factor in crop production and finally induced crop failure.

4. The question was raised as to the effect of the cylinder conditions on the availability both of the soil nitrogen and the important mineral elements phosphorus and potassium. The evidence indicated an increased loss of nitrogen and uncertainty with regard to the phosphorus and potassium, the availability of which may have been increased.

5. The suggestion was made that usual field conditions might be approached by providing each cylinder with an adjustable, vertical slot so that either a constant outlet be provided, or that run-off be allowed only at certain times or seasons of the year at the discretion of the operator.

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THE COMPARATIVE RATE OF FORMATION OF SOLUBLE MATERIAL IN CROPPED AND VIRGIN SOILS AS MEASURED BY THE FREEZING-POINT METHOD

C. E. MILLAR

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Received for publication May 27, 1919

In studies looking toward the maintenance of soil productivity, the importance of information regarding the changes a soil undergoes in passing from a virgin or fertile condition to a semi-productive state has long been recognized. Many chemical methods have been devised to measure such changes, the relative solubility of the soil constituents in water, and mineral and organic acids of different strengths being the basis of comparison. Much valuable information has been afforded by such researches, but no consistent correlation between the crop-producing power of soils and the amount of plant-food elements soluble in any of the reagents tried has been found. Recently Jordan (1) made studies of several soils of different productive power. All the common methods of analysis were made use of, including continuous leaching with water. While there appeared to be some relation between the organic matter extracted by water in one and ten-day periods, respectively and the dry matter of barley produced, the general conclusion was drawn that there was no consistent relation between the crop-producing power of the soils and either their composition as determined by total analysis or the material soluble in any of the solvents used. A review of the available literature shows this conclusion to be in accord with the findings of numerous other investigators.

It was pointed out in a previous publication (2) that the rate of formation of soluble material as measured by the freezing-point method under different conditions of moisture content and temperature was on the whole greater in a virgin than in the corresponding cropped soil. A difficulty experienced in carrying on the experiments referred to was the tendency for the concentration of the soil solution to reach a maximum and decrease within a period of 30 days. This tendency was more pronounced in the case of the virgin than of the cropped soils and consequently the concentration of the solutions tended to approach each other in this time rather than diverge, as might otherwise have been the case.

Experiments conducted with the view of ascertaining the effect of washing soils with distilled water until the concentration of the soil solution was reduced to only a few parts per million, upon the subsequent rate of formation

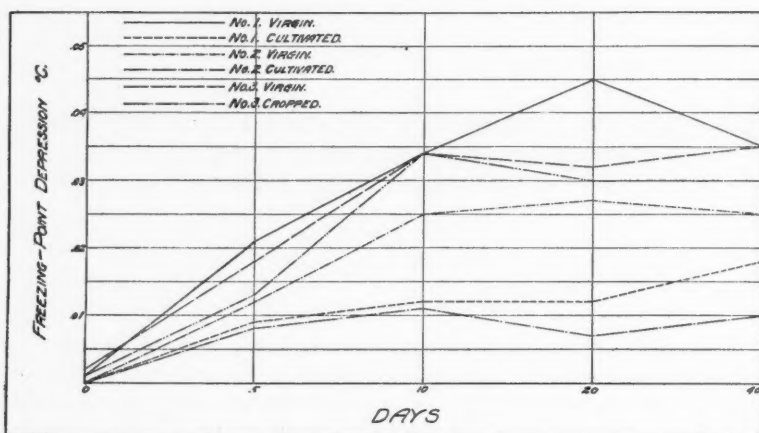


FIG. 1. DIAGRAM SHOWING THE RATE OF FORMATION OF SOLUBLE MATERIAL IN CROPPED AND VIRGIN SOILS

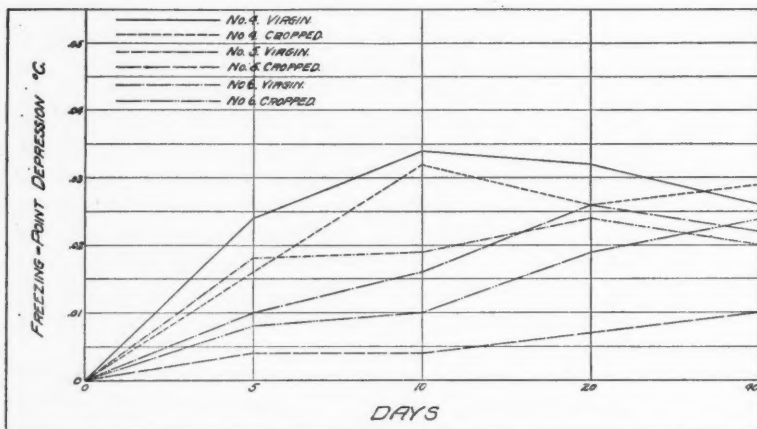


FIG. 2. DIAGRAM SHOWING THE RATE OF FORMATION OF SOLUBLE MATERIAL IN CROPPED AND VIRGIN SOILS

of soluble material, brought out the fact that when soils are so treated the tendency for the concentration of the solution to reach a maximum and then decrease is largely obviated (3). The idea, therefore, suggested itself that if the cropped and virgin soils to be compared were washed as above described and the rate of increase of the concentration of the solution measured, more accurate information regarding the rate of formation of soluble constituents might be obtained.

DESCRIPTION OF SOILS STUDIED

Six soils representing the prevailing types of upland soils in the vicinity of East Lansing were selected for this investigation. Soil 1 is a silt loam of the Miami series and represents the remains of a moraine. It has been under cultivation for 75 years or more but has been handled fairly well. Nevertheless, there has been a marked decrease in its content of organic matter and the crop-producing power has materially changed.

Soil 2 is of the same formation as no. 1. This piece of land has been handled very carelessly and is in an exceedingly poor condition.

Soils 3 and 4 are from low areas surrounded by morainic and till plain formations, respectively. These areas are small in extent and receive considerable wash from the surrounding high land. Both soils are quite high in organic matter and though they have been cropped for many years, their productivity has not appreciably decreased.

Soil 5 is a sand from a till plain area. It has been under cultivation for more than 60 years and is much depleted as a result of tenant farming. The last few years it has been receiving better treatment, and it will be exceedingly interesting to note if any change in the rate of formation of soluble material results from a continuation of this treatment.

Soil 6 is a very fine sandy loam of morainic formation. It belongs to the Miami series and has been under cultivation many years. The system of management has been good and while it is not as productive as originally, it still grows good crops and cannot be classed as a depleted or "run down" soil.

METHOD OF PROCEDURE

Seventy-five grams of air-dry soil were placed on a coarse filter paper in a funnel and washed with distilled water until the soluble material was practically all removed, as indicated by the freezing-point method. When water ceased to drain from the soil, it was thoroughly stirred and samples placed in ordinary freezing-point tubes. By this procedure the soil retained sufficient water so that a short column $\frac{1}{8}$ to $\frac{1}{4}$ inch in height stood over the soil in the tube. The tubes were stoppered and placed in a constant temperature chamber at 25°C. Shortly after the tubes were placed in the chamber the stoppers were removed for a moment to relieve any air pressure which might have developed at the higher temperature. Every few days the contents of the tubes were thoroughly stirred and the tubes allowed to remain unstoppered for a short time to allow the escape of any gas which might have accumulated. The freezing points of the soils were determined in the usual manner after 5, 10, 20 and 40 days. The data obtained are presented in table 1 and in graphic form in figures 1 and 2.

TABLE 1

Freezing-point depressions at different periods of cropped and virgin soils maintained at 25°C.; and the corresponding parts per million of soluble material

SOIL	ORIGINAL		AFTER 5 DAYS		AFTER 10 DAYS		AFTER 20 DAYS		AFTER 40 DAYS	
	Freezing point depressions	Soluble material	Freezing point depressions	Soluble material	Freezing point depressions	Soluble material	Freezing point depressions	Soluble material	Freezing point depressions	Soluble material
		p.p.m.		p.p.m.		p.p.m.		p.p.m.		p.p.m.
1. Virgin.....	0.001	25	0.021	525	0.034	850	0.045	1125	0.035	875
Cultivated....	0.000	000	0.009	225	0.012	300	0.012	300	0.018	450
2. Virgin.....	0.000	000	0.012	300	0.025	625	0.027	675	0.025	625
Cultivated....	0.000	000	0.008	200	0.011	275	0.007	175	0.010	250
3. Virgin.....	0.002	50	0.018	450	0.034	850	0.032	800	0.035	875
Cropped.....	0.001	25	0.013	325	0.034	850	0.030	750	0.030	750
4. Virgin.....	0.000	000	0.024	600	0.034	850	0.032	800	0.026	650
Cropped.....	0.000	000	0.016	400	0.032	800	0.026	650	0.029	725
5. Virgin.....	0.000	000	0.018	450	0.019	475	0.024	600	0.020	500
Cropped.....	0.000	000	0.004	100	0.004	100	0.007	175	0.010	250
6. Virgin.....	0.000	000	0.010	250	0.016	400	0.026	650	0.022	550
Cropped.....	0.000	000	0.008	200	0.010	250	0.019	475	0.024	600

DISCUSSION

The data presented show that the tendency for the concentration of the soil solution to reach a maximum and decrease before the end of the 40-day period was practically overcome by the washing. Some tendency for the concentration to decrease was exhibited by the virgin sample of soil 1 and by both the cropped and virgin samples of soil 4. The changes, however, were not sufficient to affect the conclusions.

Three of the soils studied, nos. 1, 2 and 5, showed a decidedly greater rate of formation of soluble material in the virgin than in the cropped samples. In addition, the total concentration of the soil solution was much higher in the case of the virgin samples. Of the remaining soils two, nos. 3 and 4, showed very little difference in either the rate of formation of soluble material or the total concentration of soil solution attained. It is noteworthy that these two soils are the ones which have shown very little change in productivity as a result of several years' cultivation. Soil 6 showed only a slightly greater rate of formation of soluble material in the virgin than in the cropped sample, the final concentration of soil solution being virtually the same. If the rate of increase of concentration of the soil solution under the conditions used is a criterion of the productivity of soils, one must conclude that this soil is not seriously depleted.

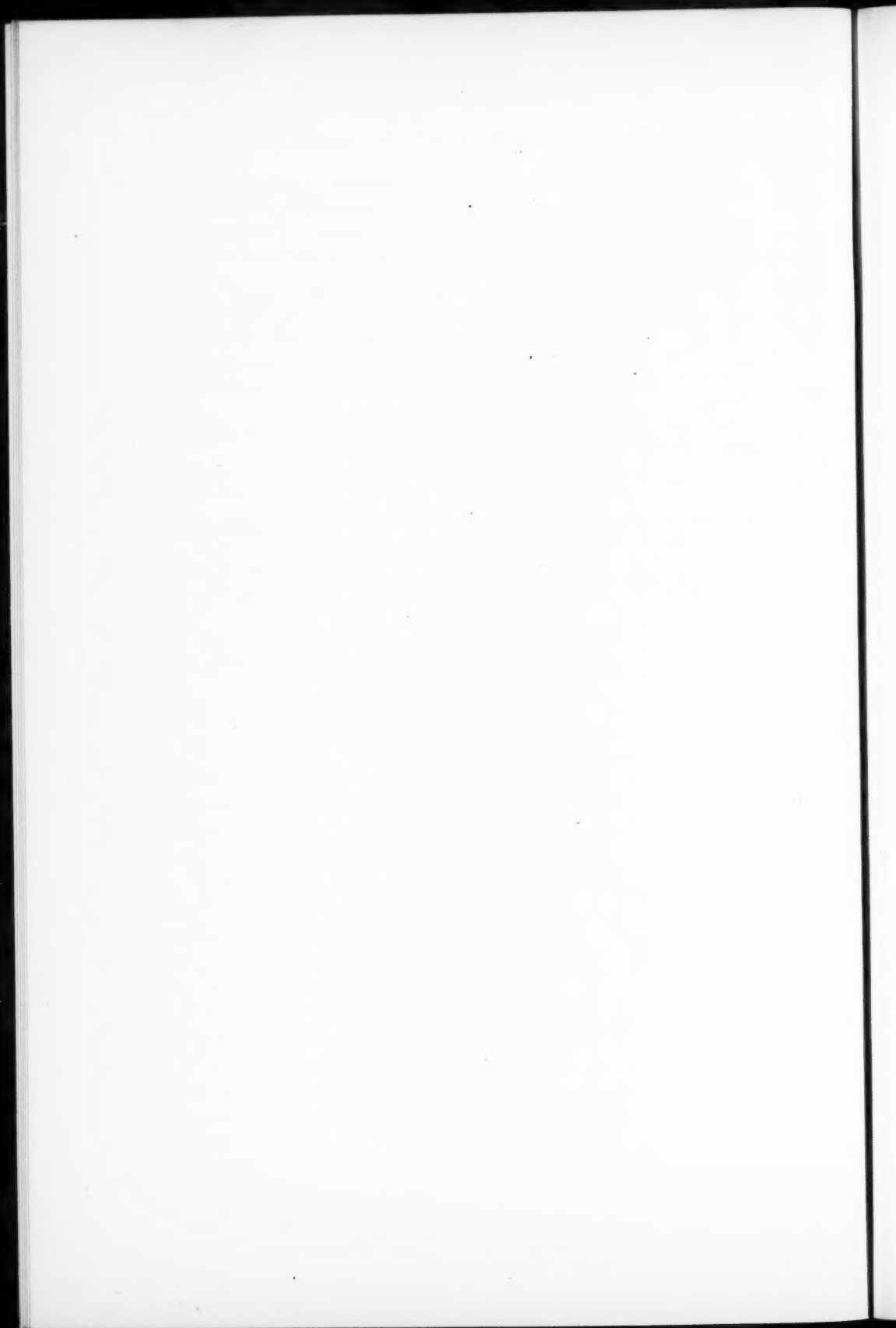
How much of this formation of soluble material is due to biological activities and how much to the direct solubility of the soil constituents, is a question which offers opportunity for much interesting research. This with other problems arising from the work presented is under investigation in the soils laboratories of the Experiment Station.

The writer realizes that the number of soils used in these experiments is small but the data are so in accord with the crop-producing power of the soils that he feels justified in suggesting that a marked decrease in the rate of formation of soluble material is one of the changes a soil may undergo as a result of several years of cultivation with the return of little fertilizing material.

The writer desires to express his gratitude to Dr. M. M. McCool for many helpful suggestions in connection with the above investigation.

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CHANGES IN COMPOSITION OF THE SOIL AND OF THE WATER EXTRACT OF THE SOIL, FOLLOWING ADDITION OF MANURE

P. L. HIBBARD¹

University of California

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These experiments were begun in the hope of discovering the effect of the addition of manure to the soil on the composition of the soil solution. This knowledge was sought for the purpose of devising a method for the rational evaluation of farm manures. The data obtained are thought to contain matter of value for the adequate understanding of the effects of manure in the soil; and also to have some practical bearing on the evaluation of manure.

DESCRIPTION OF THE FIRST EXPERIMENT

Several pounds of well-mixed fresh horse manure, consisting of wet droppings and litter, were made to pass a 10-mesh sieve by being ground through a sausage mill, and the mass again well mixed. The desired quantities were weighed out and added to weighed amounts of air-dry soil placed in 1-quart glass Mason jars. The whole was well mixed by shaking and allowed to stand for 2 hours; then the contents were passed through a 10-mesh sieve, again mixed and returned to the jars. Water was added to bring the moisture content of the mixture to 22 per cent. The jars were kept in a store-room at a temperature of 15° to 20°C. From time to time one jar of each mixture was used for analysis. Six jars of each composition were prepared. The soil used was the Yolo silty clay loam, air-dry, well sifted and mixed. After 254 days, when the last jars had been used for analysis, the remaining contents of all the jars of each mixture were mixed together and returned to a single jar; water was added to make 22 per cent; and then the contents set aside for 145 days longer, when they were analyzed. Each time the soil and manure mixtures were analyzed, a portion of the original manure was analyzed by similar methods, except that a 1 : 10 water extract of the manure was made instead of the 1 : 5 extract which was made of the soils. Three different proportions of manure were used in the soil, so that at each time analyses were made, there were 4 samples, one of the soil alone, then a 1 per cent, a 2 per cent and a 5 per cent mixture of manure with the soil. All

¹ Grateful acknowledgment is herewith made for valuable suggestions given and criticism offered by Professors John S. Burd and D. R. Hoagland, also to Mr. A. W. Christie and Mr. J. C. Martin for much of the analytical work.

data here given are from the first experiment. One per cent is equivalent to about 20 tons per acre. The methods of analysis used were in general those described by Stewart (11). The total carbon was determined by wet combustion. Total nitrogen was determined by the Gunning copper sulfate method.

DESCRIPTION OF THE SECOND EXPERIMENT

The analytical results from the first experiment were so unexpected that a second experiment was planned with the hope of overcoming difficulties which it was feared had vitiated the first experiment. The previous experiment showed much less than the expected increase of soluble matter in the soil extract due to the addition of manure, and a preliminary loss of nitrate followed by a considerable increase later. Although there was in the latter part of the experiment a gain of soluble matter, it never nearly equaled the sum of that in the soil plus that added in the manure. It was feared that an insufficient supply of oxygen was at least partly responsible for these effects. In the second experiment it was sought to avoid this possibility by using 5-gallon (11 inches in diameter, 12 inches deep) stoneware jars containing 50 pounds of soil. The jars were buried in the open ground nearly to the tops and exposed to all weather but protected from rain. Two soils were used, the Yolo silty clay loam, and the Madera sandy loam, but only one mixture of each was made, namely 2 per cent manure with the soil.² The mixtures were prepared very much as for the first experiment, being mixed dry, then placed in the pots and water added to bring to optimum moisture conditions. On account of exposure to the weather, this experiment was not as satisfactory as the first. It was necessary to add large amounts of water to maintain the proper moisture content. The addition of this water at the top of the soil eventually partially puddled the soil and apparently caused some translocation of soluble matter to the tops of the jars, due to the constant evaporation from the tops. After the experiment had continued for 3 months, this great loss of water was largely prevented by keeping the jars loosely covered.

The results were disappointing. Due to the great variation in moisture between the tops and bottoms of the jars and to the addition of much water to make up the loss by evaporation, it was found that the chemical and biological changes taking place in the soils were considerably interfered with. Nevertheless, the analytical results are quite similar to those of the first experiment, and confirm them. Primary decrease of soluble matter and loss of nitrates due to the addition of manure was followed by a gradual increase to much above that in the control soils.

None of the figures and tables here reported are taken from the results of the second experiment.

² The possibility that different soils would give different results, was the reason for using two quite different soils in the second experiment. A large difference in level of the curves for nutrients in the two soils was observed, but the curves were relatively parallel throughout, indicating similar effects consequent on addition of manure.

CARBON DIOXIDE IN THE SOIL ATMOSPHERE

It was expected that biochemical action in the soil manure mixtures would release much carbon dioxide which would increase the mineral content of the soil solutions. At the time of starting the first experiment a set of similar mixtures was made and placed in bottles so arranged that the air within them could be drawn off in order to determine its content of CO_2 . Evolution of the gas was most rapid at the beginning as soon as moisture equilibrium was attained, and gradually decreased as time went on. The amount of carbon dioxide found was somewhat proportional to the amount of manure in the mixture, but it seemed to have no relation to the minerals in the soil extract (see tables 1 and 4). Similar results as to evolution of carbon dioxide have

TABLE 1
Per cent CO_2 in air of soil-manure mixtures

TIME	MIXTURES			
	1 per cent	2 per cent	5 per cent	10 per cent
<i>days</i>				
0	12.7	13.4	26.8	28.2
1	6.2	11.4	24.6	24.5
4	15.6	22.0	32.3	37.2
6	10.7	16.8	31.2	32.8
9	11.2	18.2	31.7	35.2
18	9.5	19.8	25.8	38.8
26	8.4	15.1	22.9	36.0
31	6.1	11.8	18.7	33.6
38	7.7	13.1	22.1	35.2
45	5.8	9.9	17.0	27.0
52	5.8	9.8	15.3	30.0
59	5.8	9.6	14.6	28.3
66	5.0	8.8	13.6	28.2
73	3.6	6.6	10.0	22.1
80	3.1	6.0	9.6	21.3
87	2.7	6.5	11.1	24.0
94	2.9	5.6	8.8	17.0
101	3.2	5.6	8.9	19.0

been reported by Potter and Snyder (7), Merkle (6), and Russell and Appleyard (8). The last-named authors found increased NO_3 somewhat proportional to CO_2 in soil air, but did not consider other mineral matter as affected by CO_2 . Thus it appears that liberation of much CO_2 is not necessarily followed by great increase of solubility of soil minerals.

TOTAL CARBON

The total carbon in the soil-manure mixture decreases rapidly with time and in proportion to the amount of manure added, so that after one year the amounts remaining in the different mixtures are much more nearly alike

than at the beginning. From the manure by itself, if it is kept moist and cool, there is a large loss of carbon. This may make it appear that there has been water added because water less easily escapes in gaseous form than CO_2 . As a consequence of the loss of carbon the proportion of ash becomes greater in the remaining material. Under the best conditions there should be little loss in nitrogen, so that the manure appears to become richer in plant-food as it gradually rots away. This is a principal reason why old manure is more valuable than fresh (see table 2).

TABLE 2
Nitrogen and carbon in soil-manure mixtures. Expressed as per cent of dry substance

DAYS AFTER MIXING	PROPORTION OF MANURE ADDED TO SOIL							
	None		1 per cent		2 per cent		5 per cent	
	Nitrogen	Carbon	Nitrogen	Carbon	Nitrogen	Carbon	Nitrogen	Carbon
0	0.132	1.42	0.137	1.51	0.139	1.63	0.155	2.03
11	0.137	1.36	0.137	1.44	0.150	1.50	0.156	1.83
40	0.133	1.38	0.138	1.46	0.141	1.53	0.156	1.80
90	0.134	1.38	0.138	1.45	0.140	1.50	0.156	1.71
160	0.135	1.37	0.142	1.43	0.148	1.46	0.159	1.62
254	0.135	1.34	0.140	1.35	0.152	1.41	0.158	1.55
395	0.132	1.29	0.136	1.33	0.139	1.39	0.152	1.49

TOTAL NITROGEN AT VARIOUS TIMES

In these experiments the total nitrogen in the mixtures has not varied from first to last within the limits of accuracy of the method of analysis. In the manure itself there was an increase of the per cent of nitrogen due to the loss of carbon as above mentioned. As shown by Russell and Richards (9), loss of nitrogen gas from manure occurs only when there is alternation

TABLE 3
Water-soluble solids in manure and soil-manure mixtures. Expressed as parts per million of dry substance

DAYS AFTER MIXING	MANURE (UNMIXED)		PROPORTION OF ADMIXED MANURE							
			None		1 per cent		2 per cent		5 per cent	
	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile
0	125,920	80,280	318	223	449	295	515	374	874	585
11	146,080	100,670	366	173	508	247	438	256	699	425
40	149,330	104,400	414	174	401	201	454	153	569	301
90	134,000	85,320	695	311	578	305	659	343	683	362
160	130,760	79,248	624	309	748	357	769	351	1,024	502
254	118,900	72,400	863	436	1,080	552	1,205	552	1,610	724
395	103,740	45,360	804	436	910	523	940	529	1,410	705

TABLE 4

Composition of the water extracts of manure and soil-manure mixtures. Expressed as parts per million of dry substance

	DAYS AFTER MIXING	MANURE ALONE	PROPORTIONS OF ADMIXED MANURE			
			None	1 per cent	2 per cent	5 per cent
Ca.....	0	6,408	38.2	41.7	54.7	59.1
	11	7,227	49.9	43.4	37.1	37.7
	40	7,474	73.5	76.9	66.7	65.1
	90	6,420	69.5	69.7	70.6	71.7
	160	5,715	46.0	46.3	46.4	53.5
	254	7,830	41.8	48.6	49.0	60.2
	395	2,184	51.0	51.0	51.0	70.0
Mg.....	0	1,224	18.1	21.5	22.8	32.8
	11	935	20.3	18.7	19.6	28.1
	40	755	20.3	23.8	21.3	20.9
	90	701	23.5	22.3	24.5	25.0
	160	1,025	24.9	26.2	33.8	38.8
	254	2,160	42.5	51.8	46.9	56.3
	395	1,268	36.0	46.0	49.0	54.0
K.....	0	12,325	28.0	28.8	36.1	59.1
	11	12,833	34.6	45.4	42.5	97.3
	40	13,020	22.7	20.7	34.7	43.8
	90	13,062	36.4	37.2	37.6	42.3
	160	13,908	44.7	62.9	70.3	72.9
	254	13,950	42.5	42.8	54.5	91.8
	395	14,154	49.0	60.0	55.0	79.0
SO ₄	0	2,711	21.6	28.2	34.8	60.4
	11	3,066	31.3	31.4	35.0	56.9
	40	3,001	19.4	30.1	23.3	28.8
	90	2,428	18.5	29.2	39.0	45.8
	160	2,698	27.6	36.4	42.4	61.5
	254	1,658	62.5	35.0	43.0	67.3
	395	1,138	48.0	60.0	69.0	105.0
PO ₄	0	183	5.1	5.1	7.1	8.8
	11	187	4.5	6.7	4.0	10.1
	40	7,918	6.7	11.4	11.3	11.6
	90	6,900	5.3	7.3	8.1	12.3
	160	6,361	5.3	4.6	8.0	15.4
	254	5,380	4.7	5.2	6.8	8.3
	395	2,684	5.0	12.0	9.0	12.0
NO ₃	0		26.1	28.8	27.0	23.7
	11		55.9	8.0	4.7	4.8
	40		101.5	65.6	22.7	8.9
	90		115.2	86.3	67.2	43.7
	160		147.0	151.0	146.0	193.0
	254		286.0	324.0	345.0	413.0
	395		317.0	368.0	360.0	560.0

TABLE 4—Continued

	DAYS AFTER MIXING	MANURE ALONE	PROPORTIONS OF ADMIXED MANURE			
			None	1 per cent	2 per cent	5 per cent
Freezing-point depression.....	0					
	11		0.051	0.051	0.061	0.106
	40		0.061	0.074	0.068	0.101
	90		0.085	0.084	0.081	0.139
	160		0.083	0.098	0.100	0.147
	254		0.058	0.094	0.118	0.212
	395		0.124	0.127	0.168	0.221

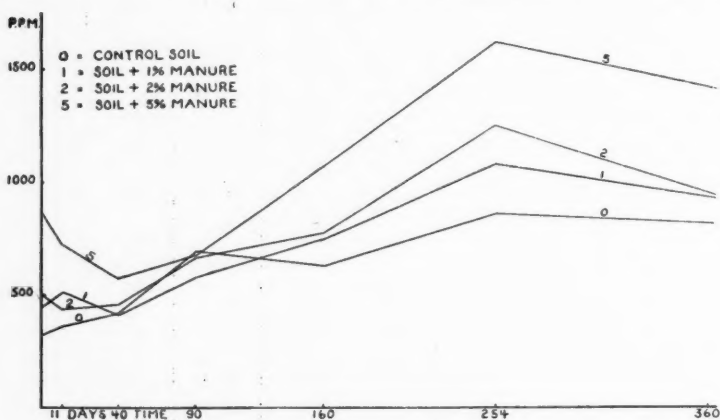


FIG. 1. DIAGRAM SHOWING TOTAL SOLIDS IN WATER EXTRACTS

of aerobic and anaerobic conditions. In the present experiments aerobic conditions were continuous, hence no loss of nitrogen was to be expected. No attempt was made to determine in what form the nitrogen existed in the mixtures, except to follow the changes in nitrate. No doubt there were considerable changes in the form of combination of the nitrogen, as argued by Sabashnikov (10). Even there may have been some loss of gaseous nitrogen with corresponding fixation by *Azotobacter*, as indicated by Hutchinson (2), but the total remained nearly constant (see table 2).

TOTAL MATTER SOLUBLE IN WATER EXTRACTS AT VARIOUS TIMES

There was in general an almost immediate notable decrease of soluble matter after addition of manure to the soil, and greater in proportion to the amount of manure added (see figure 1 and tables 3 and 4). This is a striking phenomenon when one considers that there was added in the manure more soluble matter than the soil already contained. Whether this fixation was due to physical, chemical or biological action is the subject of further

investigation. This decrease of soluble matter was considerable the day after the mixtures were made. That is, the sum of that contained in the soil and in the manure was considerably less than was actually found in the mixture (see figure 2 and table 5). After 40 days the soluble matter in the 1 per cent mixture was actually less than in the control soil. But after 160 days the reverse was true. Still at no time within 395 days was the amount of soluble matter in the mixtures equal to the sum of that found in the control soil plus that in the manure added.

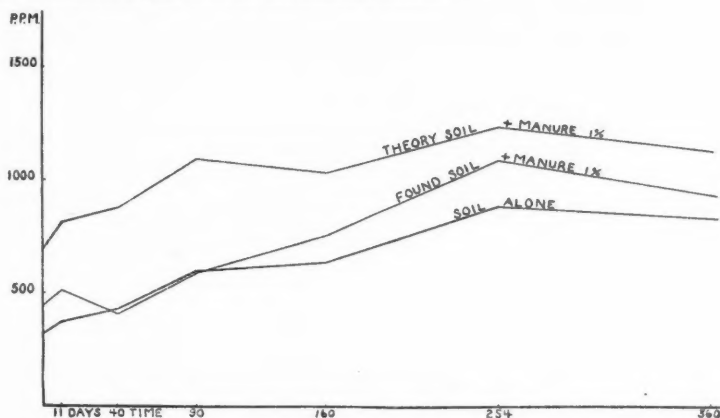


FIG. 2. DIAGRAM SHOWING FIXATION OF WATER-SOLUBLE MANURE EXTRACT BY SOIL

This fixation of soluble matter varies largely for the different ions and complexes. A large proportion of the organic matter as indicated by loss on ignition, and practically all of the potassium were fixed, also much of the calcium. Little of the magnesium and almost none of the sulfate and phosphate were fixed. A study of the annexed tables and graphs will make this more clear. These all refer to the first experiment. Very similar results were obtained in the second experiment under outdoor conditions, but on account of complications due to excessive variations in moisture, the figures are less concordant. These figures are not given, as it seemed that they shed no different light on the subject.

All these observations refer only to the water extracts, and it is not implied that exactly proportional changes necessarily take place in the real soil solution. Hoagland (1) has discussed the relationships between the water extracts and the true soil solution.

FIXATION

Fixation as above mentioned has also been observed by White (14) in working with green manures (cover crops). He explains the fixation as due to biochemical action which destroyed organic acids, liberating the mineral bases which were combined with them, thus increasing alkalinity and decreas-

ing water-soluble plant-food. Jensen's (3) experiments were not parallel with these here reported but in some respects his results confirm them.

The real cause of this fixation is still a subject of speculation.³ In the present investigation the analytical data obtained are apparently inadequate to explain it. The nitrate of the soil was quickly used up after the addition of manure, but it was too small in amount to account for much increase in alkalinity. It seems hardly possible that biochemical action could produce such effects in so short a time. Perhaps it may be due to both chemical and physical action or to one or the other alone. After some months when considerable nitrate was formed, one would expect increased solubility of bases as was found.

TABLE 5

Theoretical compared with actual total solids in water extract from soil-manure mixture. One per cent fresh manure added to air-dry soil

TIME <i>days</i>	PARTS PER MILLION IN DRY SUBSTANCE				FOUND PER CENT OF THEORY
	Manure	Soil	Sum	Found	
0	377	318	695	449	64
11	438	366	804	508	63
40	447	414	861	401	46
90	402	695	1097	578	53
160	390	624	1014	748	73
254	357	863	1220	1080	89
395	309	804	1113	910	82

Figures given express the amounts found at each of the several sampling periods as follows: Manure = amount added to soil by 1 per cent manure; Soil = amount found in control soil; Sum = arithmetical sum of manure + soil; Found = amount found in the mixture; Found per cent of theory = per cent of sum actually found.

TABLE 6

Fixation of plant-food by soil

	PARTS PER MILLION IN DRY SUBSTANCE			
	M.	S.	S. + M.	Found
Total solids.....	377.0	318.0	695.0	449.0
Loss on ignition.....	240.0	223.0	463.0	295.0
Ca.....	19.0	38.0	57.0	42.0
Mg.....	4.0	18.0	22.0	22.0
K.....	37.0	28.0	65.0	29.0
SO ₄	8.0	22.0	30.0	28.0
PO ₄	0.5	5.1	5.6	5.1

M. = amount added in manure; S. = amount found in soil; S. + M. = sum of the two; Found = amount actually found in mixture one day after mixing.

³ In another set of experiments, now in progress, in which the same manure, well rotted, was used with the same soil, very different results are being obtained. There is no loss of nitrate and less fixation of other ions than in the first experiment.

CHANGES IN NITRATE

Within one day after making the mixtures of soil and manure for the first experiment, nitrate had practically disappeared (see fig. 3). In the second experiment its disappearance was somewhat slower, possibly on account of better aeration. A gain of nitrate began after 40 days, and was most rapid in those mixtures having most manure. After 160 days nitrate in the mixture was proportional to the amount of manure added, and exceeded that in the control soil. Denitrification, loss of nitrogen as gas, has been shown by Russell and Richards (9) to occur only under alternating conditions of excess

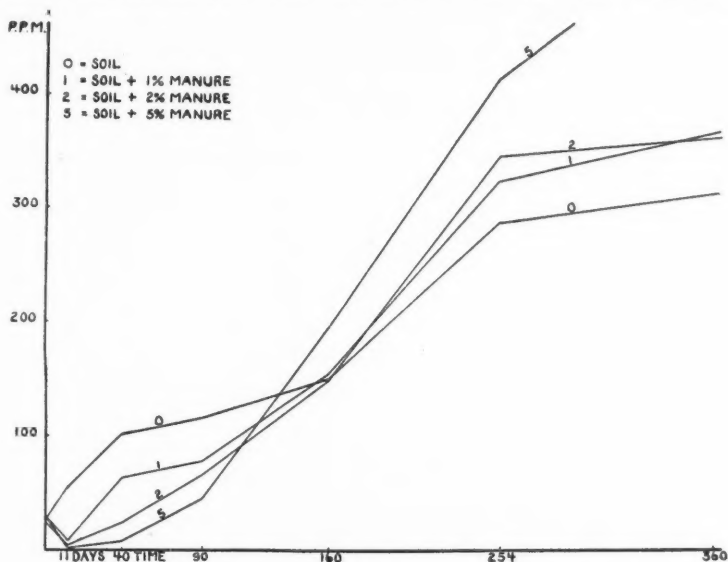


FIG. 3. DIAGRAM SHOWING NO_3 IN SOIL AND MIXTURES

or deficiency of oxygen. In these experiments it is probable that there was never a deficiency of oxygen so that that cause of loss of nitrate cannot be assumed. Others (2, 9, 10, 14) have made similar observations.

It seems most probable that the initial loss and later gain of nitrate are due chiefly to biochemical activity (14). The practical problem is so to handle and apply manure to the soil that the nitrate will be increasing at the time when the crop to be grown needs it. The primary fermentation resulting in the decrease of nitrate should have been completed before the manure is applied to the soil, so that after the mixture is made, nitrification will soon begin if it is desired to stimulate a growing crop. This explains why well rotted manure is so much esteemed by farmers. On the other hand, it may be better to apply raw manure in the latter part of the growing season in

order to furnish energy for *Azotobacter* which will thus be enabled to fix atmospheric nitrogen while the nitrogen of the manure is gradually becoming available for the next season's crop.

CHANGES IN THE COMPOSITION OF MANURE DUE TO ROTTING

The most notable of these changes is the loss of carbon with the resultant gains in the percentage of other constituents. In some cases it has been observed that there was an actual increase of moisture in the rotted manure which would indicate that the CO_2 escaped more rapidly than water (see table 7).

TABLE 7

*Percentage composition of manure used in experiment 1 at each sampling period on the water-free basis**

TIME	ASH	ORGANIC	NITROGEN	TOTAL CARBON
<i>days</i>				
0	15.3	84.7	1.55	41.9
11	15.7	84.3	1.55	42.1
40	15.5	84.5	1.60	42.0
90	15.8	84.2	1.56	42.0
160	16.7	83.3	1.57	42.0
254	17.6	82.4	1.72	41.3
395	18.2	81.8	1.88	41.1

* The original manure at time of mixing contained 70.3 per cent water, 0.305 total P_2O_5 ; and 0.424 total K_2O .

CHANGES IN THE COMPOSITION OF THE MANURE EXTRACT

Soluble organic matter in the manure decreases as rotting proceeds as might be expected, since this soluble matter is composed of the most easily fermentable constituents, but the soluble mineral matter increases as rotting proceeds, though after 3 months some of the ions began to decrease. Notable increases are in soluble phosphate and ammonia. These changes are apparent in table 8. The decrease in soluble Ca and Mg is probably due to the increase in alkalinity from the change of organic nitrogen to ammonia. Soluble sulfate (SO_4) decreased somewhat regularly, perhaps because of changing from organic to inorganic combination.

CHANGES IN ALKALINITY

Changes in hydrogen-ion concentration caused by the change of organic nitrogen, phosphorus and sulfur to their mineral acid forms are probably adequate to account for the increased solubility of calcium, magnesium and potassium as pointed out by White (14). When changed from the ammonia form to the nitrate form, 14 pounds of nitrogen would release acid enough to neutralize

100 pounds of calcium carbonate. Since the nitrogen is present largely in organic combination at first, when it changes to ammonia, a notable increase of alkalinity must occur. On changing to nitrate, this alkalinity would be replaced by an equal acidity which would displace CO_2 and perhaps silicic acid with the formation of soluble nitrates of calcium, magnesium, sodium and potassium. Phosphorous and sulfur when oxidized would greatly increase acidity. Though these changes in acidity appear to be theoretically probable, no determinations were made in order to follow them.

TABLE 8

Composition of manure extract from the same sample at successive sampling periods

TIME <i>days</i>	PARTS PER MILLION REFERRED TO WATER-FREE SUBSTANCE							
	Total solids	Loss on ignition	Ca	Mg	K	N as NH_4	SO_4	PO_4
0	125,920	80,280	6,408	1,224	12,325	340	2,711	183
11	146,080	100,670	7,227	935	12,833	1,740	3,066	187
40	149,330	104,400	7,474	755	13,020	1,740	3,001	7,918
90	134,000	85,320	6,420	701	13,062	2,690	2,428	6,900
160	130,760	79,248	5,715	1,025	13,908	4,210	2,698	6,361
254	118,900	72,400	7,830	2,160	13,950	5,100	1,658	5,380
395	103,740	45,360	2,184	1,268	14,154	4,410	1,138	2,684

INCREASE OF PLANT-FOOD

Russell and Appleyard (8) have shown that after temperature and moisture, which are most important, the chief factors governing the increase of plant-food in soils are, numbers of bacteria, nitrate and carbon dioxide which run parallel. Tottingham (13) found an increase of nitrogen due to the addition of straw to manure and assumed it to be caused by the extra supply of energy furnished by straw to the nitrogen-fixing bacteria. Jensen (3) found increase of plant-food due to the action of mineral-free organic solvents. Organic matter with calcium carbonate gave a greater increase than without calcium carbonate on sandy soil; on clay soil the reverse was true. Lipman and Blair (4) and Potter and Snyder (7) have also obtained some such results. Thorne (12) has maintained that the value of manure lies almost solely in the additional plant-food which it furnished the soil. If the gain of water-soluble mineral matter following the application of manure is simply additive, his position seems to be well taken. The present experiments, as shown by table 4, show that the effect of fresh manure is not simply additive, but that the soluble matter is less than the sum of that in the soil and in the added manure. It is known that *Azotobacter* may fix atmospheric nitrogen when supplied with a carbohydrate source of energy. In this way the soil would be enriched by the addition of manure by more than the

amount of plant-food in the manure. In these experiments there is no evidence of such fixation of nitrogen. Also, it might be expected that after the addition of manure, the increased acidity due to the change of nitrogen to nitrate, phosphorous to phosphoric acid and sulfur to sulfate would increase Ca, Mg, Na and K in the soil solution. Results of these experiments do not indicate such effects. They offer no ground for disputing the correctness of Thorne's position, that manure is valuable chiefly or solely for the plant-food it contains. As to the correctness of Thorne's position, the writer does not here offer any opinion.

On the other hand, it may be pointed out that considering the short duration of the present experiments, and the small increase in nitrate, together with the practically constant total nitrogen, the manure had not yet had time to produce its most notable and valuable effects. General experience and notably the historic experiments at Rothamsted support the view that the effect of manure, especially when applied in large amounts, is only gradually apparent and may endure for some years.

SUMMARY

1. Fresh manure was mixed with soil in the proportions of 1, 2 and 5 per cent, the mixtures kept in loosely covered glass jars at optimum moisture, and analyzed from time to time with the following results.
2. Carbon dioxide in the soil atmosphere was increased in proportion to the manure added.
3. Total carbon gradually decreased and more rapidly for larger amounts of manure.
4. Total nitrogen was constant from the first to the last of the experiment.
5. Total water-soluble matter was within a few weeks decreased in the 1 per cent mixture to below that in the control soil. After that it gradually increased to considerably above that in the control soil, but never to equal the sum of that in the control soil plus that in the added manure. The 2 and 5 per cent mixtures showed relatively greater decreases and increases.
6. Further investigation of the cause of the observed fixation is necessary in order to explain it adequately.
7. These changes were not relatively the same for the different ions and complexes.
8. In the soil extract, there was less change of Ca and Mg than of K, SO_4 and NO_3 .
9. Nitrate at first quickly disappeared, and later increased considerably over that in the control soil. These changes are ascribed to biochemical action.
10. Increase in water-soluble mineral matter after the addition of manure to soil can be accounted for largely by that derived from the mineral matter of the manure itself.

CONCLUSIONS

1. When fresh manure is mixed with soil the resulting reaction decreases the amount of water-soluble plant-food, so that crops started at that time might be retarded, or at least not immediately benefited by the manure. When the manure becomes well decomposed it adds materially to available plant-food. Consequently, fresh manure should not be added to a soil just previous to or during the time a crop is growing.

2. If the soil is kept sufficiently open to the air, there should be no loss of nitrogen due to the addition of manure.

3. Liberation of large amounts of CO_2 in the soil by rotting manure does not always greatly influence the composition of the water extract of the soil.

4. The water-holding capacity and porosity of soil are undoubtedly improved by manure, quite apart from increase in soluble plant-food, but the latter is increased chiefly or solely by the amount added in the manure, and very little due to reactions set up by the manure in the soil.

5. The conclusions here drawn are strictly applicable only to these experiments. Since the conditions were quite unlike those obtaining in the field, it may be possible that field experiments would show quite different results.

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THE COMPARATIVE VALUE OF VARIOUS FORMS OF LIMESTONE

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The beneficial effect of the use of lime has been fully realized in America only within the last few years. Some of the older experiment stations, among them Pennsylvania, Maryland, and Rhode Island, were the first to demonstrate the benefit derived from liming the soil, and both Pennsylvania and Maryland also emphasized the feasibility of using ground limestone for this purpose. The work of the Illinois Experiment Station has demonstrated the great value of ground limestone on acid soils. There are some questions, however, regarding the use of limestone upon which additional information is needed: viz.,

1. Can dolomitic limestone be used successfully on acid soils, and what is its value compared with high-calcium limestone?
2. What is the comparative value of the finely ground material and that more coarsely ground, which can be purchased more cheaply?
3. What is the durability of the various forms and kinds of lime when applied to soils in the field?
4. What effect does the application of limestone to the surface have upon the acidity of the subsurface and the subsoil?
5. What is the annual loss of limestone from the soil, and what are the factors which contribute to this loss?

COMPARATIVE EFFECT OF HIGH-CALCIUM AND DOLOMITIC LIMESTONE

Since 1912, the experimental farm at Newton, Jasper County, Illinois has been devoted primarily to a study of these questions.

The comparative value of high calcium and dolomitic limestone was studied on 114 plots on this farm by applying both kinds of limestone in varying amounts and degrees of fineness, including burnt lime. This experimental farm was established in 1912. In 1916, three and a half years after the initial application of limestone to the soil, samples of the soil were collected and submitted to careful chemical analysis for residual limestone and acidity.

The results, obtained by averaging the data from all plots, 15 plots in each case receiving equivalent applications of the same kind of limestone irrespective of the degree of fineness, are recorded in table 1.

The amount of residual limestone found was, as an average, distinctly larger where dolomitic limestone had been added; that is, this form of stone was more lasting in the soil. However, notwithstanding its more lasting quality, it was fully as effective in destroying the soil acidity as was the high-calcium limestone. In every case where high-calcium limestone had been applied, the average results showed a smaller amount of residual limestone, a larger annual loss of limestone, and less acidity destroyed. The data also show that the larger the amount of limestone applied, the more residual carbonate was found, the more acidity was destroyed, and the larger was the loss of limestone from the surface soil.

TABLE 1

Comparative effect of high-calcium and dolomitic limestone (including burnt lime)—Newton Field, 1916

Average pounds of calcium carbonate in 2,000,000 pounds of surface soil (one acre about 0 to 6 $\frac{1}{2}$ inches deep)

S E R I E S	AVERAGE OF ALL SERIES			
	High calcium	Dolomitic	High calcium	Dolomitic
	Limestone found		Annual loss	
Lime applied				
	<i>pounds</i>	<i>pounds</i>	<i>pounds</i>	<i>pounds</i>
Light application.....	499	725	392	304
Medium application.....	1,095	1,330	849	777
Heavy application.....	3,005	4,035	1,599	1,258
Average annual loss.....			946	779
Acidity destroyed				
Light application.....	628	708		
Medium application.....	936	947		
Heavy application.....	1,396	1,562		
Net average annual loss.....			967	554

EFFECT OF DEGREE OF FINENESS

The effect of the degree of fineness of limestone upon the loss of limestone and upon the acidity in the surface soil is shown by a study of the results found in table 2. The figures are obtained by averaging the data from all plots which received like applications of both the high-calcium and the dolomitic limestone. (The results are the averages of six separate determinations from as many separate plots.)

In general, the finer the stone, the greater was the loss of limestone. The mill-run stone ($\frac{1}{4}$ inch down) was practically as effective as any grade in destroying the acidity and in addition possessed better lasting qualities. The fine material present in this grade of stone seems to be sufficient for the

immediate requirements of the soil, and the residual properties are of value in maintaining an alkaline reaction in the soil. An important point brought out clearly in the above table is that the annual loss of limestone is dependent upon the amount of limestone applied to the surface. The loss of limestone is roughly proportional to the amount applied and varies only from 14 to 16 per cent of the total amount applied to the surface.

TABLE 2
Effect of degree of fineness of limestone

Average pounds of calcium carbonate in 2,000,000 pounds of surface soil (one acre about 0 to 6 inches deep)

	FINENESS				
	$\frac{1}{2}$ inch down	$\frac{1}{4}$ to $\frac{1}{10}$ inch	$\frac{1}{10}$ inch down	$\frac{1}{50}$ inch down	Burnt lime
Limestone found					
Light application.....	pounds 617	pounds 1,151	pounds 631	pounds 272	pounds 392
Medium application.....	1,613	2,117	1,025	659	648
Heavy application.....	3,899	4,776	3,558	3,545	1,822
Acidity found					
Light application.....	289	356	322	450	395
Medium application.....	437	222	367	468	348
Heavy application.....	75	64	110	136	56
Acidity destroyed					
Light application.....	631	620	709	637	746
Medium application.....	863	1,059	925	855	1,006
Heavy application.....	1,368	1,443	1,458	1,492	1,634
Average annual loss of limestone					
Light application.....	358	208	331	482	385
Medium application.....	721	523	871	995	953
Heavy application.....	1,351	1,080	1,419	1,417	1,869

EFFECT OF LIMESTONE ON ACIDITY OF SUBSURFACE

The results from the Newton experimental field are not conclusive in showing any marked effect upon the acidity of the subsurface. The limestone applied to the surface undoubtedly does have some effect in neutralizing the acidity of the subsurface, but it is an exceedingly slow process and requires the lapse of considerable time after the initial application of limestone to the surface. The complete destruction of the acidity even in the surface soil is a slow process since even the heavier applications of limestone upon the Newton field after the lapse of three and a half years had not been sufficient to destroy completely all the acidity in the surface soil. This is undoubtedly due to the difficulty of thoroughly mixing the surface soil and

the applied limestone under ordinary systems of cultivation, such as are generally practiced on the average farm.

The effect of the limestone applied to the surface soil upon the destruction of the acidity of the subsurface is shown clearly by the results obtained from the Odin experimental field. Samples of soil were taken from this field 14 years after the initial application of limestone. It was found that all the acidity of the surface had been destroyed except in one or two instances; also that the acidity of the subsurface had been appreciably decreased by the application of limestone to the surface. The effect of the applied limestone on the acidity of the subsurface is recorded in table 3.

TABLE 3

Effect of limestone on subsurface soil. Averages of all plots, series 100 to 400: Odin Field, 1917
Average pounds of calcium carbonate in 4,000,000 pounds of subsurface soil (one acre about 6½ to 20 inches deep)

NUMBER OF PLOTS	LIME ADDED TO SURFACE SOIL	LIMESTONE FOUND	ACIDITY		LIMESTONE NET GAIN FOR SUBSURFACE
			Found	Destroyed	
16 plots	None	pounds None	pounds 3,703	pounds	pounds
24 half-plots	Light application	451	2,735	968	1,419
24 half-plots	Heavy application	1,083	1,834	1,869	2,952

As a result of the application during 14 years' time the sum of the limestone destroyed in neutralizing acidity in the subsurface and that found remaining in that stratum amounted to 2952 pounds where the heavy application had been made and 1419 pounds where the light applications had been made. These figures represent an annual gain of 211 pounds and 94 pounds of limestone, respectively, in the subsurface stratum. If these numbers be subtracted from the annual loss from the surface soil, the unaccounted annual loss from that stratum amounts to 601 pounds and 484 pounds, respectively, for the heavy and the light applications.

THE EFFICIENCY OF A TON OF LIMESTONE

The amount of limestone which may be economically added to an acre at any one time is limited. Two questions, therefore, of very great importance to the farmer are: (1) What is the maximum amount which may be economically used? (2) What becomes of the applied limestone and how long does it last in the soil? The data presented show that the annual loss of limestone is dependent upon the amount added. When the ¼-inch mill-run product was used the annual loss was 14 per cent of the application. From the data presented in table 2 the rate of the loss of limestone for the various applications may be readily calculated. Such calculations are made for the two kinds of limestone used and are recorded in table 4.

The data from the Odin field clearly show that 1 ton of limestone applied every 4 years maintained the soil in an alkaline condition. This fact, together with the data presented in table 4, seems to indicate that this rate of application is the more desirable one to use after the initial acidity has been destroyed.

TABLE 4
Residual limestone in treated soil

RATE OF APPLICATION	REMAINING AT THE END OF					
	First year	Second year	Third year	Fourth year	Fifth year	Sixth year
High calcium limestone						
1 ton per acre.....	pounds 1,184	pounds 870	pounds 556	pounds 242	pounds	pounds
2 tons per acre.....	2,572	1,893	1,214	535		
4 tons per acre.....	5,604	4,325	3,046	1,767	488	
Dolomitic limestone						
1 ton per acre.....	1,191	948	705	462	219	
2 tons per acre.....	2,619	1,998	1,376	754	132	
4 tons per acre.....	5,744	4,738	3,732	2,726	1,720	714

CONCLUSIONS

1. From the evidence thus far secured, it appears, that for the common farm land of acid regions, an application of 1 ton per acre of limestone once in 3 or 4 years is sufficient to keep the soil alkaline, or sweet, after the initial acidity has been destroyed by heavier applications.

2. Dolomitic limestone can be used successfully on acid soils. It is slightly more effective than high-calcium limestone in neutralizing the soil acidity, is more durable, and has no injurious effects on the crop yields.

3. As the result of nearly 4 years' work on the Newton field, there is no evidence that finely ground limestone is more effective in correcting soil acidity than is the total product from a $\frac{1}{4}$ -inch screen, which contains both the finer material for immediate use and the coarser material for greater durability. This "mill-run" product seems to be the most economical form to use; but final conclusions must await further data concerning crop yields.

4. The destruction of the acidity of the soil is not a rapid process, for it is dependent upon the complete mixing of the applied limestone with the surface soil, which is a slow process. Limestone applied to the surface slowly penetrates into the subsurface. This process, however, requires considerable time. On the Odin field after 14 years, one-half the acidity in the subsurface was neutralized where the larger applications had been made to the surface, and one-fourth where the lighter applications had been made. Applications of limestone to the surface soil seem to have no effect upon the acidity of the subsoil. The amount of native limestone found in the subsoil is a

variable quantity. In some cases there is none present even at a depth of 40 inches, whereas in other cases it extends upward even slightly into the subsurface.

5. The annual loss of limestone from the soil depends upon a number of factors, among which are the kind, the form, and the amount added. The data presented show that the annual loss of limestone is not so large as generally assumed. As an average of all determinations, the annual loss from the surface 20 inches was 760 pounds per acre from the Newton field and 542 pounds per acre from the Odin field. A study of the total calcium indicates that the actual loss of bases may have been less than is shown by these figures, which are based upon the carbon dioxide and acidity determinations.

6. It is very evident from the data presented that chemical analysis may be depended upon to measure the acidity in the soil, the reduction in acidity due to the action of limestone applied, and also to find the limestone still remaining in the soil, whether from applications made or from a supply native to the soil.

LIME REQUIREMENTS AS DETERMINED BY THE PLANT AND BY THE CHEMIST¹

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The soil used represented the surface soil taken to the depth of plowing. Some of that taken in June, 1916, was sent upon request to F. P. Veitch, then referee on soils for the Association of Official Agricultural Chemists. He planned to submit it in part for coöperative work on chemical methods for determining "lime requirements."

The results by the numerous available methods are influenced by such different factors that it seemed desirable to conduct pot experiments with kinds of plants which are markedly favored by liming, in order that a basis might be available for forming a judgment of the practical value of the chemical methods.

The samples were taken to represent the permanent plats 23, 25, 27 and 29 of the Rhode Island station. The treatment which these plats had received to the close of 1914, and other information concerning them, is given in Bulletin 160 of the station. Subsequently, miscellaneous crops were planted in 1915 and 1916. In the spring of 1915, plat 23, called the unlimed ammonium sulfate plat, for the first time was given an application of hydrated lime equivalent to 500 pounds of calcium oxide per acre; plat 25, 1500 pounds; and plat 29, 1000 pounds. Plat 27 has never been limed.

Liberal amounts of nitrogen, phosphorous and potassium have been added annually to each plat alike since 1893. To plats 23 and 25 the nitrogen was supplied in sulfate of ammonia and to 27 and 29 in nitrate of soda. The physiological acidity and basicity of the respective forms of nitrogen have been shown plainly in the crop results.

The soil was air-dried, sifted through about 2-mm. holes and, after removing samples for Mr. Veitch, 12 pounds placed in each 8-inch Wagner pot. So-called c. p. calcium oxide was hydrated with an equivalent amount of water and passed through a 200-mesh sieve in preparation for liming certain pots. Special attention was paid to bringing about as complete a reaction as possible between the soil and the lime with the hope of obtaining the maximum effect of the lime for the immediate crop. The applications of lime and

¹ Contribution No. 241 from the Agricultural Experiment Station of the Rhode Island State College. Presented at the Convention of the Association of Official Agricultural Chemists in 1916.

fertilizers were mixed thoroughly with the moist soil at intervals during two weeks before planting early Egyptian beet seeds on July 28, 1916; the crop was harvested November 6, 1916. The basic nutrients were proved to be optimum by additional pots receiving calcium in sulfate, and extra potassium, nitrogen and phosphorus. The results are presented in table 1.

TABLE 1
Relation of the lime requirements to the effect of lime on beets

CaO ADDED PER ACRE	WEIGHT OF BEET ROOTS, AVERAGE FROM TWO POTS				CaO REQUIREMENTS PER ACRE AFTER THE GROWTH OF BEETS			
	Unlimed (NH ₄) ₂ SO ₄ plat	Limed (NH ₄) ₂ SO ₄ plat	Unlimed NaNO ₃ plat	Limed NaNO ₃ plat	Unlimed (NH ₄) ₂ SO ₄ plat	Limed (NH ₄) ₂ SO ₄ plat	Unlimed NaNO ₃ plat	Limed NaNO ₃ plat
<i>pounds</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>pounds</i>	<i>pounds</i>	<i>pounds</i>	<i>pounds</i>
None	0	211	37	386	7,800	5,800	7,300	5,100
378				352				5,100
757		300		418		5,600		5,000
1,135	83	311	308	434	6,900	5,500	6,000	5,000
1,513	210	364	313		6,700	5,100	5,400	
1,892	248		365		6,500		5,300	
2,270	318				5,000			
3,780	351				5,000			
<i>Before the growth of beets:</i>								
Ammonia method					6,900	5,200	5,500	3,700
Veitch method					8,700	5,800	8,100	4,800

The ammonia method was used in general in determining the lime requirements given in this paper. It may be found in Soil Science, v. 6, p. 405-511.

In November, 1916, a new lot of soil was taken from the same plats and a second experiment conducted in a manner similar to the first, except that instead of beets, cos lettuce was planted February 3, 1917. The crop was harvested April 26, 1917. The results given are in table 2.

TABLE 2
Relation of the lime requirements to the effect of lime on lettuce

CaO ADDED PER ACRE	WEIGHT OF GREEN LETTUCE, AVERAGE FROM TWO POTS				CaO REQUIREMENTS PER ACRE AFTER THE GROWTH OF LETTUCE			
	Unlimed (NH ₄) ₂ SO ₄ plat	Limed (NH ₄) ₂ SO ₄ plat	Unlimed NaNO ₃ plat	Limed NaNO ₃ plat	Unlimed (NH ₄) ₂ SO ₄ plat	Limed (NH ₄) ₂ SO ₄ plat	Unlimed NaNO ₃ plat	Limed NaNO ₃ plat
<i>pounds</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>gm.</i>	<i>pounds</i>	<i>pounds</i>	<i>pounds</i>	<i>pounds</i>
None	0	36	12	143	8,300	6,200	6,400	4,800
500				160				
1,000		168	147	181		5,600	5,800	4,700
1,500	74	163	180	162	7,300	5,300	5,500	
2,000	157	182	181		6,400	5,000	5,200	
3,000	174				6,200			
4,000	201			142	5,800			2,800

By reference to tables 1 and 2 it may be seen in general that after maximum crops had been attained by liming, the soil still showed a lime requirement of about 5000 pounds; in fact, the lettuce, although a crop which is very sensitive to "soil acidity," was depressed in growth when an application equivalent to 4000 pounds of calcium oxide was made to the limed nitrate of soda soil, and the subsequent lime requirements thereby reduced to 2800. A carbon-dioxide determination made in this soil showed that not more than about 10 per cent of the added lime remained in carbonate at the end of the experiment.

At the bottom of table 1 are the lime requirements of the soil before it was used in the beet experiment. It may be seen that the limed nitrate of soda soil had a lime requirement of 3700 by the ammonia method and yet not much advantage was derived from liming. When about this amount was added for lettuce there was less crop than where smaller amounts were used. And yet it may be seen that the Veitch method yielded even higher results than the ammonia method.

Although some very interesting correlations could be shown between the lime requirements as determined by the plant and by the chemist, it is desired rather to refer sufficiently to certain results obtained at the Rhode Island station, so that the chemist will not make the mistake of associating lime requirement too closely with soil acidity,² and of giving too little attention to the varying characteristics of different kinds of plants as related to other deleterious factors. Only a very brief reference to the indications afforded by our work should be made in this connection. The details will be given elsewhere, with such modifications as the terse statements here made for the sake of brevity may require.²

As illustrating the importance of considering the plant in its relation to the soil, let us consider rye and barley seedlings. They are affected alike by acidity, and yet very differently by acid soils. Under field conditions where rye is not benefited by liming, barley is increased many fold. The aqueous extract of the soil affects the two seedlings similarly as the soil, as do also the ignited residues when brought into solution. Aluminum is a prominent constituent of the residue. When to nutrient solutions this element is added as aluminum sulfate, for example, in comparison with equivalent amounts of sulfuric acid, the two seedlings are depressed alike by the acid, whereas the aluminum sulfate, although it causes a depression in the growth of the barley similar to that with the acid, has comparatively little effect on the rye.

Emphasis has been laid heretofore on the toxicity of aluminum salts because of their hydrolysis and consequent effect on the acidity. The extent of the hydrolysis was sufficient to produce in the nutrient solution only about one-fourth the hydrogen-ion concentration that was produced by the equivalent

² Hartwell, Burt L., and Pember, F. R. 1918. The presence of aluminum as a reason for the difference in the effect of so-called acid soil on barley and rye. *In* Soil Sci., v. 6, p. 259-278.

amount of acid. The greater part of the depression in the growth of barley therefore was attributed largely to the aluminum itself rather than to the acidity produced by the hydrolysis of its salts, whereas the aluminum is much less toxic to rye.

Accordingly, the elimination of the effect of the aluminum in acid soils seems likely to prove of more importance than the neutralization of the acidity, and attention should be given to methods of determining active aluminum while we are also developing those for soil acidity. Perhaps the principal materials for rendering aluminum inactive in the soil will prove to be lime and acid phosphate. Especially the latter substance has been shown to decrease the amount of aluminum soluble in carbonated water and dilute acetic acid. Its application in large amounts to a soil in which crops greatly benefited by liming are to be grown, may enable those crops to make a satisfactory growth. For example, in the lettuce experiment described previously some of the soil from the unlimed ammonium sulfate plot was thoroughly mixed in a moist condition with large amounts of acid phosphate in addition to the phosphorus added in the basal manures for nutrient purposes. The mixture was allowed to react about two weeks previous to planting the lettuce. The crop could make no growth on the check soil, but 74 gm. per pot were produced with acid phosphate at the rate of 14 tons per acre, and 272 gm. when used at the extraordinary rate of 28 tons. By reference to table 2 it may be seen that the next largest yield in the entire experiment was 201 gm., which was where lime equivalent to 2 tons of calcium oxide per acre was applied to the same soil. Nevertheless, at the close of the experiment the lime requirements were found to be 12,000 pounds of calcium oxide per acre where the larger amount of acid phosphate was used, 9000 where half the amount was used, 8300 for the check soil where only the basal nutrients were added, and 5800 where the 2 tons of calcium oxide were applied.

A substance which increased the high lime requirement at least for a time so changed a very acid soil that an application of lime was unnecessary.

THE AMMONIA-FIXING CAPACITY OF CALCIUM SULFATE

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INTRODUCTION

That much nitrogen is lost from manure by the volatilization of ammonium compounds is generally conceded. The extent to which this loss can be prevented by the use of chemicals as preservatives is not well established. The use of calcium sulfate for this purpose is a very old practice. Concerning its efficiency as an ammonia fixer there is little agreement among investigators. There is also a difference of opinion among those who believe it will conserve ammonia as to the manner in which it does it.

Some agriculturists have entertained the view that calcium sulfate has the ability to hold ammonia gas by physical adsorption. Some have contended that the retention of the ammonia may be due to a process of chemical absorption, resulting in the formation of a double sulfate. Far the greater number have considered that the benefit from using calcium sulfate as a preserver depends upon its ability to transform volatile ammonium carbonate into the more stable ammonium sulfate by the process of double decomposition.

According to the results of Haskins (8) physical adsorption plays a very small part, if any, in the fixation of ammonia.

The work of Bell and Taber (3) makes the second of these suppositions appear untenable, since all the conditions necessary to the formation of $\text{CaSO}_4 \cdot (\text{NH}_4)_2\text{SO}_4 \cdot x(\text{H}_2\text{O})$ would not obtain in a manure heap.

The third assumption, that of double decomposition, is based on rather reasonable grounds both theoretical and experimental. However, the degree to which the reaction takes place in decomposing organic matter is questionable. Since the reaction is a reversible one, and since calcium sulfate is comparatively insoluble, it would appear doubtful whether under the normal moisture conditions in manure, very much ammonium sulfate is formed before a state of equilibrium is reached. Even after being formed, if some of the moisture is lost in any way, the reverse reaction very probably predominates and produces again some of the unstable ammonium carbonate. It is well known that when $(\text{NH}_4)_2\text{SO}_4$ and CaCO_3 are mixed together intimately in the dry state, or at least with only hygroscopic moisture present, a distinct odor of ammonia is noticeable. Obviously this is due to the formation of volatile $(\text{NH}_4)_2\text{CO}_3$. It is also easy to believe that changes of temperature and other physical conditions may have a great influence on the direction in which

the reaction proceeds. Reactions with gypsum in a pile of fermenting material are no doubt somewhat complicated. Sulfates, being oxidizing substances, are likely to be reduced to sulfides by the action of the carbonaceous matter present. The sulfides formed may interact with H_2CO_3 to form carbonates.

HISTORY OF INVESTIGATIONS

Considerable investigational work has been carried on to determine the power of calcium sulfate to fix ammonia. In most cases gypsum in variable quantities has been mixed with manure, allowed to stand for a time, and by analysis of the manure for nitrogen before and after the investigation a conclusion has been reached as to the value of the gypsum as a preservative. The fact that much of the nitrogen is given off in a free state, as shown by Russell and Richards (17) as well as by other investigators (6) has been little considered. A few experiments of a modified type have been carried on.

Although many of these investigations have only a general bearing on the problem under consideration, it seems desirable to review briefly some of the results that have been obtained and some opinions and conclusions that have been reached.

The earlier writers on agriculture have said much regarding the ability of calcium sulfate to fix ammonia. Boussingault (4) states that M. Shattermann, who was a large horse keeper of Alsace during the first half of the nineteenth century, managed large heaps of manure very well and used either sulfate of iron or gypsum as preservatives.

Liebig (9) believed that the beneficial effects which were observed where calcium sulfate had been strewn on a meadow were due to the ability of the salt to fix the ammonia of the atmosphere by the formation of ammonium sulfate. He describes an experiment which was made with growing beans and peas on a garden plot, which had been well manured and strewed with gypsum. Before beginning the experiment it was found by analysis that both soil and gypsum were quite free from carbonates; but on examination of some of the salt taken from the surface of the ground after several weeks, it was discovered that the greater part of the gypsum had been converted into the carbonate of lime and that the soil to a depth of six inches effervesced strongly on the addition of acid. This corresponds to the results obtained by Spatzier and reported by Storer (18). Lemmerman and Fresenius (11) record similar results.

From an extended investigation covering 6 years of time, on how to reduce the loss of nitrogen from manure, Müntz and Girard (13) concluded that the use of chemical agents is unsatisfactory and that, in the case of calcium sulfate, so much must be used to attain the desired result as to make the practice uneconomical.

Burri, Herfeldt and Stutzer (5) inoculated nutrient solutions with manure bacteria, some with bacteria from old decomposing liquid manure and some with bacteria from fresh liquid. Various manure preservatives were added to

the cultures and results noted. One of their conclusions was that "gypsum has no value as a preservative. It does not combine with the carbonate of ammonia already present and does not prevent the further formation of this substance even when used in large quantities."

Aeby, Dorsch, Matz and Wagner (1) found that in case of complete humification and long storage the denitrifying action in manure is lessened by being reinforced with gypsum, but concluded that as a fixer of ammonia it is of little use.

Aso and Nishimuro (2), in studies on the comparative value of superphosphate of calcium, gypsum and kainit as manure preservatives found that gypsum and kainit are much inferior to superphosphate as fixers of ammonia.

Lindsey (10) reviewed the results of German investigators and found the consensus of opinion to be against the use of chemical preservatives such as gypsum, on the ground that the nitrogen saved is quite out of proportion to the expense involved.

Pichard (15) compared the action of calcium sulfate and ferrous sulfate in conserving soil nitrogen. The substances were mixed with artificial soils of known composition and placed in enameled earthenware pots. The gypsum, which was added at the rate of 5 gm. per kgm., was found to be more favorable to nitrification and a more effective conserver of nitrogen than ferrous sulfate.

At the Ohio Agricultural Experiment Station (21) work has been carried out to determine the effect on crops of the use of reinforced manure. The manure was applied at the rate of 8 tons per acre, in a 3-year rotation of corn, wheat and clover, and the reinforcing materials were used at the rate of 40 pounds to the ton of manure. In the trial with gypsum-treated yard manure the increase over untreated manure was 7.37 bushels of corn and 473 pounds of stover, 4.07 bushels of wheat and 452 pounds of straw and 581 pounds of hay. In the trial with stall manure the increase was 3.18 bushels of corn and 211 pounds of stover, 2.35 bushels of wheat and 201 pounds of straw, but with a loss of 134 pounds of hay. These are the averages for 16 crops of corn, 16 of wheat and 13 of hay. The results of 5 years' analyses of treated and untreated manure used in these tests, before and after 3 months' exposure to winter weather, showed a nitrogen loss of 29.6 per cent when reinforced with gypsum and 35.5 per cent when no preservative was used (20).

Dietzell (7) placed samples of manure in 12-liter flasks carrying tubes through which a current of air could be drawn. Gypsum and other preservatives were mixed with different samples. The temperature at which the flasks were kept ranged from 10.5° to 25°C. Analysis was made of the manure at the beginning and at the end of the experiment to determine the nitrogen content. The ammonia which passed out through outlet tubes was collected by means of standardized sulfuric acid. Gypsum and kainit proved to be the most efficient preservatives tried in preventing the loss of nitrogen. It was also found that, if the air is excluded from manure, no preservative is needed to

conserve the nitrogen. This corresponds with the recent conclusion of Russell and Richards (17) that the nitrogen loss from manure is least when stored under anaerobic conditions.

Meyer (14) investigated the effect of various preservatives on 100-cc. portions of liquid manure. He found that from 92.8 to 95.9 per cent of the nitrogen of the liquid was in the form of ammonium carbonate, and that it was practically all lost when allowed to stand for some time exposed to the air. Approximately 50 per cent of the nitrogen was saved when gypsum was used as a preservative.

Severin (19) sterilized manure and inoculated it with cultures of manure bacteria. By using 4 per cent of gypsum as a preserver he succeeded in reducing the loss of ammonia by approximately one-half. He also noted a faster decomposition of the manure treated with gypsum than of that not so treated. The greatest loss observed, however, when no CaSO_4 was used was only 0.0739 gm. from 265 gm. of manure in 90 days. Not only was it concluded that gypsum is an efficient preserver of ammonia but also that the value of acid phosphate for this purpose is due to the calcium sulfate it contains.

Palmer (16) carried out an investigation similar in many respects to that of Severin but the quantities of manure were greater and his purpose was only to determine the efficiency of various chemicals as preservatives of ammonia in manure. Fifty-four pounds of horse manure or 150 pounds of cow manure were placed in galvanized iron cans. The chemical preservatives were added at the rate of 80 pounds to the ton of manure. In the case where CaSO_4 was used 32.53 mgm. of nitrogen was lost from 100 pounds of cow manure in 62 days as compared to 52.47 mgm. when no preservative was added. In the trial with horse manure 32.08 mgm. was lost in 44 days compared to 73.18 mgm. when no CaSO_4 was used.

The majority of investigators seem inclined to the view that gypsum possesses some virtue as a nitrogen conserver. The way in which this is done and the quantitative effect are still unsettled problems.

NATURE AND PURPOSE OF THIS EXPERIMENT

Most, if not all, of the attempts to determine the capacity of CaSO_4 to fix ammonia in manure have involved the use of decomposing organic matter and urine as the source of the ammonia. Since many and complicated biochemical reactions take place in a mass of fermenting manure, and since the quantity of ammonia and ammonium carbonate actually formed is not known, it seems desirable to investigate the ammonia-fixing ability of CaSO_4 independent of decomposing organic matter, using as the source of the ammonia a definite quantity of pure ammonium carbonate. In this way many troublesome factors are eliminated. The number of possible reactions also is limited and the actual capacity of CaSO_4 to hold the ammonia of ammonium carbonate by the process of double decomposition of these salts can, it would seem, be more definitely estimated.

EXPERIMENTAL PROCEDURE

Four trains of bottles were arranged as shown in figure 1. The size of the bottles marked A was 2.5 liters. In each of these was placed 250 gm. of filter paper, which had been previously pulped fine and dried, as a substitute for the organic matter of the manure. With the filter paper added to each of two of these bottles, 150 gm. of pure CaSO_4 was intimately mixed. The material in the bottles was compacted and 750 cc. of a solution containing 39.30 gm. of $(\text{NH}_4)_2\text{CO}_3$ was added to each. This amount of $(\text{NH}_4)_2\text{CO}_3$ would be equivalent to 9.645 gm. of nitrogen or 19.29 pounds to the ton of material. The water content was made approximately 75 per cent. The CaSO_4 was added at the rate of 300 pounds to the ton of material. The temperature was varied

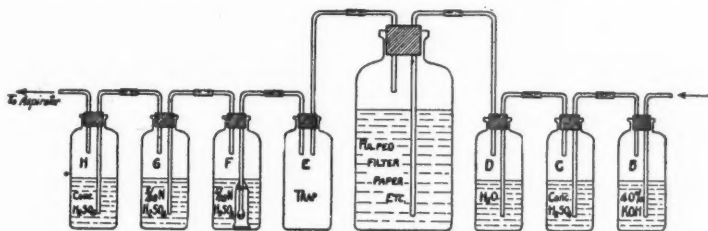


FIG. 1. DIAGRAM SHOWING ARRANGEMENT OF APPARATUS USED IN EXPERIMENT

from time to time, as will be seen by reference to tables 1 and 2. Temperatures higher than room temperature were obtained by placing the bottles marked A inside a box lined with asbestos and heated with an electric lamp. Lamps of different candle power were used to obtain the different degrees of heat. By this arrangement it was possible to control the temperature to within a comparatively narrow range. The ammonia which escaped was collected in standard acid solutions in bottles F and G.

The bottles marked C and H contained concentrated H_2SO_4 to absorb the ammonia of the air. Bottle B was partly filled with a 40 per cent solution of KOH to remove the CO_2 from the incoming air and bottle D contained distilled water to insure the entrance of sufficiently moist air to maintain the water content of A. Air was aspirated through the apparatus from time to time for 10-minute periods, the actual number of aspirations being shown in table 1.

DISCUSSION OF RESULTS

It will be noted by an examination of the results of the experiment as summarized in tables 1, 2, and 3 that quite a large amount of nitrogen was given off during the period of the test by bottles containing no CaSO_4 . In those treated with CaSO_4 the quantity given off was 79.7 per cent less. This was a much larger saving of nitrogen than was found by either Severin (19) or

TABLE 1
The effect of CaSO₄ in preventing nitrogen loss

NUMBER OF DAYS	NUMBER OF ASPIRATIONS	RANGE OF TEMPERATURE	NITROGEN LOSS	
			Without CaSO ₄	With CaSO ₄
		°C.	gm.	gm.
9	4	20°-25°	A. 0.0240	A. 0.0055
			B. 0.0180	B. 0.0030
15	8	20°-25°	A. 0.0460	A. 0.0005
			B. 0.0410	B. 0.0015
11	6	20°-30°	A. 0.0754	A. 0.0074
			B. 0.0764	B. 0.0079
20	19	20°-30°*	A. 0.2510	A. 0.0240
			B. 0.2560	B. 0.0200
12	12	45°-55°	A. 0.1870	A. 0.0250
			B. 0.2620	B. 0.0270
10	10	50°-59°	A. 0.3940	A. 0.0310
			B. 0.3090	B. 0.0270
9	15	65°-70°	A. 0.7420	A. 0.1150
			B. 0.6260	B. 0.1420
5	10	65°-90°‡	A. 0.7520	A. 0.1120
			B. 0.7045	B. 0.1050
4	7	80°-85°	A. 0.8467	A. 0.2565
			B. 0.8485	B. 0.2510
			A. 0.0105†	A. 0.0090†
			B. 0.0100†	B. 0.0095†
			A. 2.6150‡	A. 0.4900‡
			B. 2.1500‡	B. 0.6200‡
95	91		A. 5.9436	A. 1.0749
			B. 5.3014	B. 1.2139
			Average, 5.6225	Average, 1.1419

* Temperature for one day of period was over 30°C.

† Ammonia collected in bottles marked G during period of test.

‡ Ammonia absorbed by water condensed in trap bottles.

§ Temperature was 65°-70° during 4 days of period and raised to 90° one day.

Palmer (16), the former having found that CaSO₄ reduced the loss approximately 50 per cent and the latter 38 per cent in the case of cow manure and 56.2 per cent in the case of horse manure. It will be recalled, however, that the quantity of NH₃ given off in their experiments was quite small, due partly to the fact that they depended on the decomposition of manure for the ammonia supply and partly, no doubt, to a lower temperature.

It may be thought that the temperature to which the mixture of filter paper, (NH₄)₂CO₃, etc., was raised in the latter part of this investigation was too high to be analogous to the conditions in a manure heap. While it is true that ordinarily the temperature of manure is not so high, it was found by Russell and Richards (17) that the temperature of fermenting horse manure under cover may rise to 70-80°C. It seemed desirable, therefore, to note the results

at high temperature in order to determine the efficiency of CaSO_4 as a preservative under such conditions.

The quantity of nitrogen given off by the two bottles of a pair is quite different in some cases, especially at the higher temperatures. This can be largely accounted for by the difficulty experienced in keeping the source of heat at the same distance from the bottles of the mixture.

A comparatively large quantity of the nitrogen evolved was absorbed as ammonia by water condensed in the trap bottles. No condensation of mois-

TABLE 2
Daily nitrogen loss with and without CaSO_4

PERIOD	TEMPERATURE	WITHOUT CaSO_4	WITH CaSO_4
	°C.	per cent	per cent
First.....	20°-25°	0.024	0.006
Second.....	20°-25°	0.030	0.001
Third.....	20°-30°	0.072	0.007
Fourth.....	20°-30°	0.132	0.011
Fifth.....	45°-55°	0.197	0.023
Sixth.....	50°-59°	0.365	0.030
Seventh.....	65°-70°	0.854	0.148
Eighth.....	65°-90°	1.511	0.225
Ninth.....	80°-85°	2.197	0.659

Note: The ammonia absorbed in trap bottles and that neutralized in bottles marked G is not included in these calculations.

TABLE 3
Total nitrogen loss with and without CaSO_4

PERIOD	TEMPERATURE	WITHOUT CaSO_4	WITH CaSO_4
		per cent	per cent
During first 55 days.....	Room temperature	4.08	0.33
During last 40 days.....	45°C. and above	54.21	11.50
Total loss 95 days.....		58.29	11.84

ture was noticeable in these bottles until the beginning of the fifth period, when the temperature of the mixture was raised above room temperature. In compiling table 3, therefore, it was thought well to consider that all ammonia collected in the trap bottles was given off during the last forty days.

A consideration of the results as shown by the tables would seem to leave little doubt that CaSO_4 will hold some ammonia and that it does it by interacting with $(\text{NH}_4)_2\text{CO}_3$ to form the non-volatile compound $(\text{NH}_4)_2\text{SO}_4$. This last assumption is based on the probability of other reactions being prevented by the conditions under which the experiment was performed. It is very probable that many reactions take place in a manure heap, subsequent to the formation of $(\text{NH}_4)_2\text{SO}_4$ that would result in an ammonia loss. One of these is the possi-

ble reduction of sulfates to sulfides by the carbonaceous matter present. We know, too, that the reaction $(\text{NH}_4)_2\text{CO}_3 + \text{CaSO}_4 = (\text{NH}_4)_2\text{SO}_4 + \text{CaCO}_3$ is reversible and that it is largely a question of mass action as to which direction the reaction will go.

When a large amount of water is present the formation of $(\text{NH}_4)_2\text{SO}_4$ takes place until equilibrium is reached. When the percentage of water is lowered the reverse reaction no doubt predominates. When the state known as "fire-fanged" is reached in a manure-heap, under which condition a comparatively small percentage of water is present, it would seem reasonable to believe that most of the ammonia of the $(\text{NH}_4)_2\text{SO}_4$, that had been formed, would be changed to the carbonate and be lost. A plentiful supply of moisture, therefore, seems necessary, if CaSO_4 is to be of real service as a manure preservative. Such a condition obtained in this experiment and also in those of Severin and Palmer. It is perhaps the reason also that Meyer (20) found gypsum able to hold practically half the ammonia of liquid manure. It would seem desirable to investigate the amount of ammonia given off during a few weeks of time from a mixture of filter paper, $(\text{NH}_4)_2\text{SO}_4$ and CaCO_3 at comparatively high heat and low moisture content.

An examination of the table will show that CaSO_4 apparently loses some of its ability to hold ammonia as the temperature is raised. The relative amount held at high temperature is not as great as at low.

SUMMARY AND CONCLUSIONS

It appears to be unquestionable that CaSO_4 will prevent to a certain degree the loss of ammonia from a mixture containing volatile $(\text{NH}_4)_2\text{CO}_3$ and it is quite probable that the loss prevention is due to the formation of non-volatile $(\text{NH}_4)_2\text{SO}_4$ by the double decomposition of $(\text{NH}_4)_2\text{CO}_3$ and CaSO_4 , for no other means is thought to be possible under the conditions of this experiment.

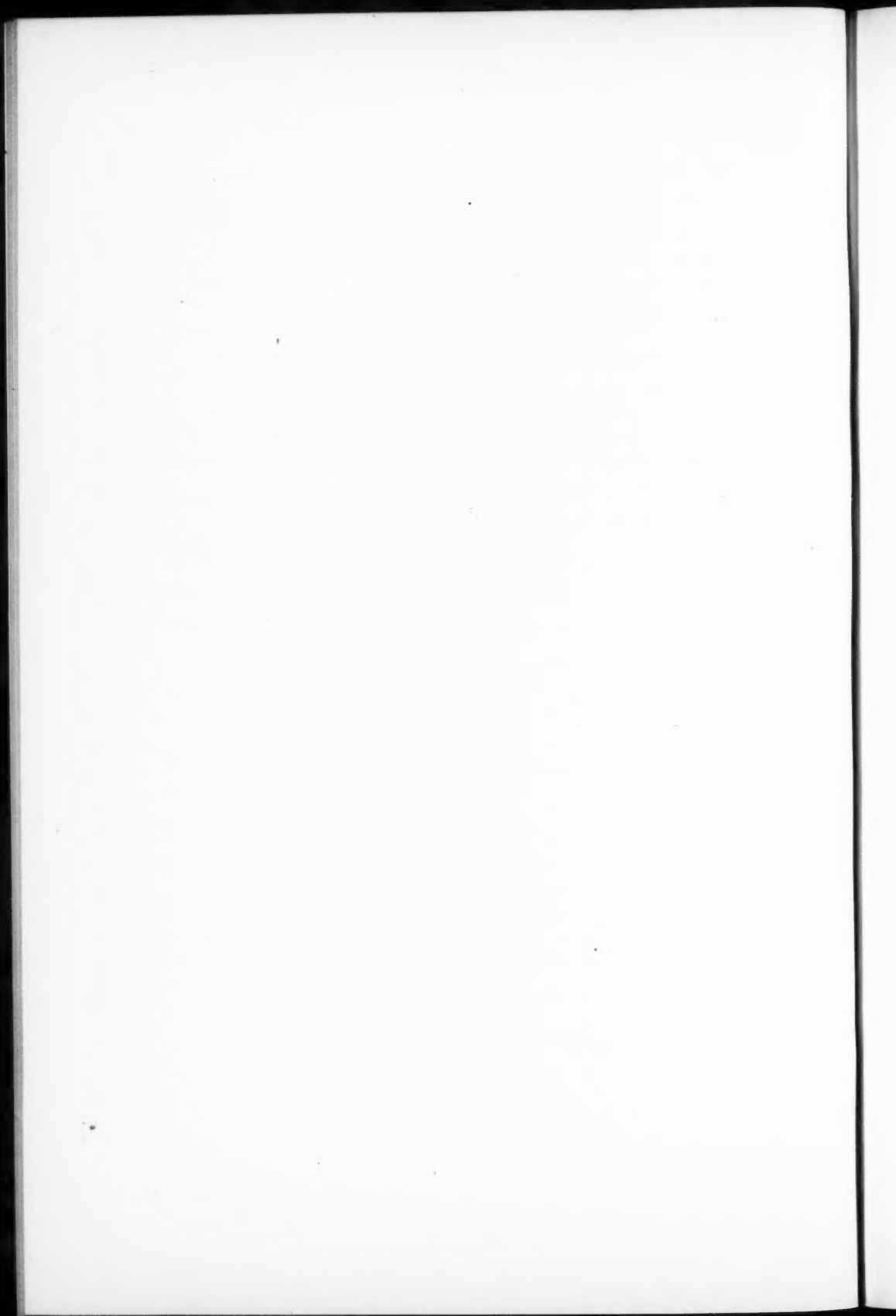
The ammonia-fixing capacity of CaSO_4 is apparently dependent on the temperature. The quantity of ammonia given off by the $(\text{NH}_4)_2\text{CO}_3$ increases as the temperature rises and the percentage of it held by the CaSO_4 decreases.

A treatment of 300 pounds of CaSO_4 to the ton of manure would, no doubt, effect a pronounced ammonia fixation, if the water content were comparatively high. Whether subsequent reactions that probably take place in a manure heap would prevent its remaining fixed and whether the practice of reinforcing manure with gypsum is economical are questions beyond the scope of this investigation.

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PARALLEL FORMATION OF CARBON DIOXIDE, AMMONIA AND NITRATE IN SOIL

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The biological significance of carbon-dioxide formation in the soil has long been recognized and its measurement under varying conditions has attracted the attention of many students of soil biology. Potter and Snyder (2) have recently reviewed the literature relative to this subject. Similarly, the vast amount of literature relative to ammonia and nitrate formation in soils attests the importance attached by students of soil biology, to a better understanding of the factors controlling these very important processes.¹ It has long been recognized that to a large extent the processes through which carbon dioxide, ammonia and nitrates are formed in soil are biological in nature. The fact that the formation of any one of these compounds may take place independently of the others, has resulted in each process being studied more or less independently of the others. There are few instances on record where the parallel formation of carbon dioxide, ammonia and nitrates in a soil has been studied.

When the experiments herein described were undertaken it was proposed to carry out rather extensive investigations along this line. Other work, however, necessitated an indefinite delay, so that the publication of the results of a few of the more suggestive experiments that have been completed seems desirable at the present time.

METHODS

Any one who has attempted to make quantitative measurements of carbon dioxide evolved continuously over a considerable length of time realizes the difficulties to be overcome in making such measurements accurately. In soils, the difficulties are many times multiplied.

Since these experiments were carried out (late in 1916 and early in 1917) several methods, perhaps more accurate for measuring carbon dioxide evolved from soils, have been suggested by other investigators. However, the methods employed gave, as a rule, consistent results, and duplicate determinations agreed as well as could be expected.

The question of whether the air used to sweep the carbon dioxide out of the soil should be drawn over or through the soil has often been raised. The writer is of the opinion that so long as the production of carbon dioxide and

¹ The results presented in this paper on ammonia and nitrate formation are not such as will necessitate a general consideration of previous work along similar lines.

the consumption of oxygen are not greatly stimulated by the addition of easily oxidized organic matter, drawing air over the soil will remove carbon dioxide and keep up a sufficient supply of oxygen to maintain aerobic conditions. However, if the column of soil is of considerable depth and the evolution of carbon dioxide and the consumption of oxygen are as rapid as in these experiments, it is questionable whether aerobic conditions can be maintained unless the air is drawn through the soil. It is also questionable, if the air is simply drawn over the soil, whether the removal of carbon dioxide will be sufficiently rapid for the records to indicate the rate of formation. For these reasons the air was drawn through the soil in all experiments here reported.

Figure 1 represents a complete unit of the apparatus used and needs little explanation. The soil was placed in a calcium chloride cylinder, a perforated porcelain plate preventing the soil from falling into the foot of the cylinder. The cylinder was then connected through the side opening, by means of glass tubing, to a small wide-mouth bottle containing a 10 per cent solution of sodium hydroxide. Into the stopper of this bottle was also placed a straight-form calcium chloride tube 1 inch in diameter, the larger bore being 10 and the smaller bore 4 inches long. This tube was filled nearly full with solid glass beads. The bottle contained such a quantity of 10 per cent solution of sodium hydroxide that when suction was applied the liquid drawn into the tube would cover about three-fourths of the beads. The tube containing beads was in turn connected with another bottle and tube similar in every respect except that it contained a dilute acid. The acid should be of such a strength that an even moisture content will be maintained in the cylinder of soil to which the bottle containing acid is connected.

Six such units were usually connected in a series. The air before entering the first cylinder was passed through sodium hydroxide and acid wash towers similar to those used for catching carbon dioxide and ammonia. The whole was connected with a water pump. Between the last cylinder and the pump was placed a trap sufficient in size to release the partial vacuum in case of a lowered water pressure. If there is danger of irregularity in suction a third wash tower, containing a solution of sodium hydroxide, so arranged that the current of air passes through in the reverse order, can be introduced between the acid wash tower and the succeeding cylinder of soil. This would increase the necessary suction only slightly and would prevent any carbon dioxide from a cylinder of soil being caught by a wash tower to the rear. With wash towers arranged as indicated no liquid can be drawn backward in case of accidental reversal of the air current.

With six such units connected to one pump the resistance to the current of air and the total volume of air under partial pressure are such that an even flow of air bubbles was not obtained but rather an intermittent passage of bubbles through the various wash towers. This has the advantage of bringing about frequent changes of liquid in the wash towers.

The quantity of carbon dioxide caught was measured by thoroughly washing the beads with carbon-dioxide-free water and determining the carbon dioxide present by the double titration method. Ammonia caught in the acid wash towers can be determined by distillation or by the aeration method. In no instance in the experiments herein reported was the quantity of ammonia given off sufficient to be taken into consideration. This was true even though the quantity of nitrogen present as ammonia was often more than 30 mgm. in 100 gm. of soil.

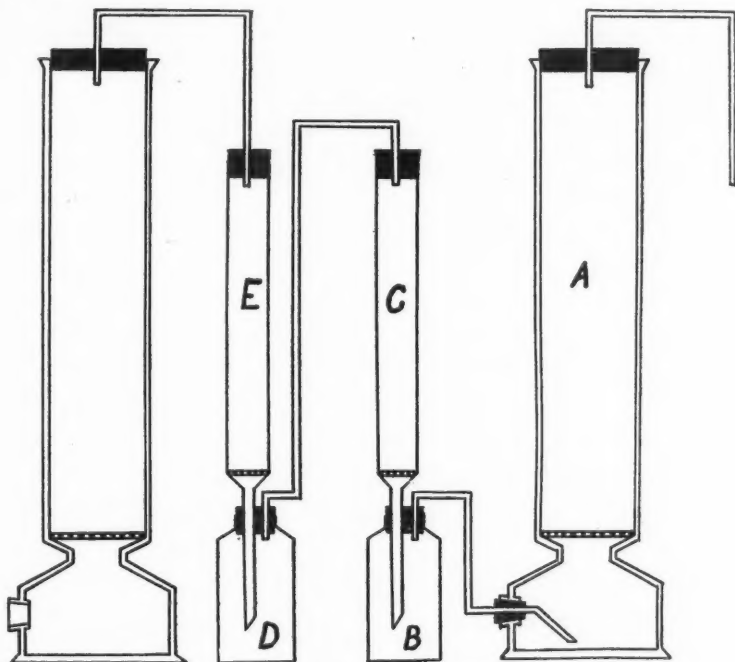


FIG. 1. A UNIT OF APPARATUS USED IN EXPERIMENTS

a, Calcium chloride cylinder containing soil; *b*, bottle containing 10 per cent NaOH; *c*, calcium chloride tube containing glass beads; *d*, bottle containing dilute acid; *e*, calcium chloride tube containing glass beads.

A sufficient quantity of soil was removed from the top of the cylinder at each analysis to make duplicate quantitative ammonia and nitrate-nitrogen determinations. For the former, analyses were made by the aeration method. Nitrate nitrogen was determined by extracting with water and using either the colorimetric or aluminum reduction method. The carbon-dioxide content of the soil was not taken into consideration.

Carbon dioxide is reported in milligrams given off between the various analyses, a correction being made upon a basis of the initial quantity of soil. Am-

monia and nitrates are reported in milligrams of nitrogen per total quantity of initial soil. The curves for carbon dioxide are constructed by adding the total quantity given off prior to any particular analysis. In most instances cylinders of soil were run in duplicate or triplicate, and the curves in such instances are based upon averages. It occasionally happened that an analysis, particularly of carbon dioxide, was evidently incorrect, possibly because of a leak in the system. Such records were discarded.

The same soil, a silt loam of approximately the following composition was used in all experiments: coarse grades of sand 0.9 per cent; fine grades of sand 8.4 per cent; silt 71.8 per cent; and clay 17.8 per cent. The water-holding capacity of this soil in loose condition is approximately 54 cc. per 100 gm. of soil.

EXPERIMENTAL DATA

Experiment A, recorded in table 1 and figure 2, was run to determine how closely the duplicate carbon-dioxide determinations would check. Six 1000-gm. samples of soil containing 20 gm. of water per 100 gm. of soil were weighed

TABLE 1

Experiment A. CO₂ production in soil with (samples 3-6) and without (samples 1-2) 1 per cent cottonseed meal

SAMPLE	CO ₂ EVOLVED DURING THE PERIODS INDICATED IN DAYS										
	1	2	3	4	5	6-7	8-9	10-11	12-14	15-17	Total
	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
1	165	149	198	195	97	156		231*		183†	1,374
2	136	129	182	129	100	136	178			172	1,164
3	1,726	2,380	1,945	1,202	791	885	671	414	348	347	10,709
4	1,928	2,614	1,969	1,364	830	1,113	816	458	416	394	11,902
5	1,829	2,436	1,951	1,257	813	974	664	414	348	332	11,018
6	1,809	2,446	1,839	1,169	818	948	704	481	387	321	10,922

* Eighth to eleventh day.

† Twelfth to seventeenth day.

out. To two samples no further additions were made. These were placed in cylinders 1 and 2. To the remaining four 1 per cent cottonseed meal was added and thoroughly mixed. These samples were placed in cylinders 3 to 6. Air was drawn through the soil continuously for 17 days except when analyses were being made. For the first few days carbon-dioxide analyses were made daily at the same time of day; afterwards the period between analyses increased as the quantity of carbon dioxide evolved decreased. No analyses of ammonia and nitrate nitrogen were made in this experiment.

An examination of the carbon dioxide curves, figure 2, will show that the evolution of carbon dioxide was very uniform, giving exceptionally regular curves. Since all subsequent experiments received an addition of cottonseed meal or dried blood, the curves in this experiment for soil with no addition need not

be considered further. The agreement between duplicates is also considered good. For example, the probable error for the analyses on the fifth day is ± 1.00 and for the total carbon dioxide evolved during the 17 days ± 1.58 .

There was a very rapid formation of carbon dioxide during the first few days; the maximum apparently occurring during the second 24 hours. This may possibly be due to the fact that the day the experiment was begun cannot be regarded as a full 24 hours, since it required at least half a work-day to set the

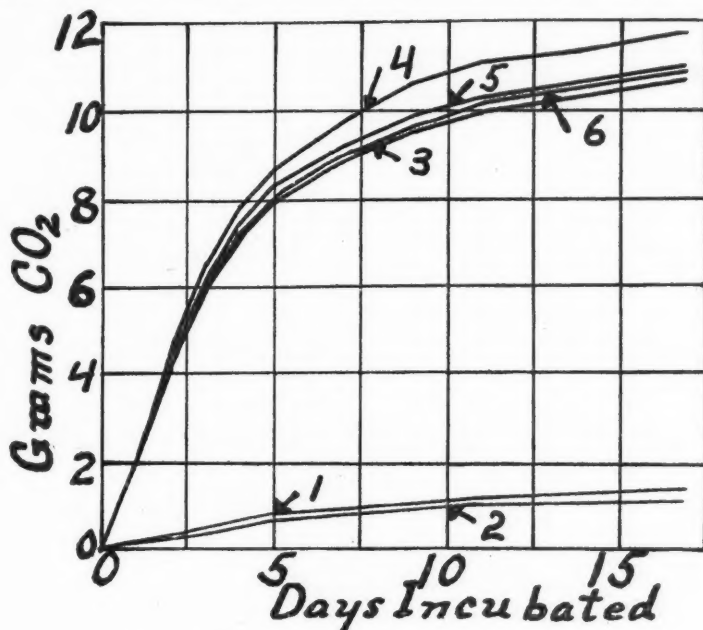


FIG. 2. CARBON DIOXIDE FORMATION IN EXPERIMENT A

Samples 1 and 2: No cottonseed meal added. Samples 3 to 6: 1 per cent cottonseed meal added. Moisture content 20 cc. per 100 gm. soil. Aerated continuously.

experiment up. By the end of 3 days 50 per cent and by the end of 7 days 75 per cent of the total carbon dioxide given off during the course of the experiment had been evolved. After the first week the quantity given off decreased very rapidly, the curves soon assuming the form of straight lines. For convenience the carbon dioxide curves of this experiment will be spoken of as normal or typical carbon-dioxide curves.

EFFECT OF VARYING THE MOISTURE CONTENT

Experiment B, recorded in table 2, and figure 3, was performed to study the effect of varying the moisture content upon parallel carbon dioxide, ammonia, and nitrate formation in soil. One thousand grams of soil containing 1 per

TABLE 2
Experiment B. Formation of CO₂, ammonia and nitrates in soil containing varying quantities of moisture; 1 per cent cottonseed meal added

DAYS	MILLIGRAMS OF CO ₂ AND NITROGEN AS NH ₃ AND NO ₃ PER 1000 GM. OF SOIL														
	No. 1; 12 cc. H ₂ O			No. 2; 22 cc. H ₂ O			No. 3; 32 cc. H ₂ O			No. 4; 42 cc. H ₂ O			No. 5; ? cc. H ₂ O		
	NO ₃ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.
1	1,958	19.5	0	2,161	50.5	0	2,585	37.5	0	2,295	34.2	0	2,018	27.7	0
2	2,260	48.9	0	3,200	152.4	0	3,254	153.2	0	2,651	93.0	0	2,744	121.4	0
3	1,674	111.1	0	1,626	241.8	0	1,846	222.2	0	1,668*	233.7	0	1,528	245.1	0
4	1,087	141.1	0	854	281.1	Trace	958	281.7	Trace	1,087	258.2	0	1,100	264.7	Trace
5	962	197.7	Trace	481	297.4	5.4	784	317.0	6.8	770	267.9	Trace	839	323.5	4.5
6	264	194.4	4.5	513	300.6	6.8	287	295.7	11.4	360	276.2	3.4	396	277.8	5.6
7-8	436	201.0	6.1	220	310.5	11.3	251	312.1	23.5	353	289.2	6.8	353	294.1	18.0
9-10	309	214.0	9.0	277	302.3	14.9	157	277.8	27.0	152	305.6	16.9	237	217.0	33.8
11-12	220	227.0	11.3	55		18.0	90	326.8	45.0	165	274.0	24.6	137	294.0	33.9
13-15	128	262.4	13.5	73	325.2	23.5	73	303.9	54.1	153	269.5	54.1	124	317.0	64.9
16-22		212.9	15.0		247.9	27.0		255.6	67.5		218.9	79.2		209.4	91.8
23-28	284	159.4	27.2	78	219.0	38.7	96	190.0	93.4	154		108.0	124	130.4	122.4

* Estimated.

cent cottonseed meal and the following quantities of water were placed in the corresponding cylinders: no. 1, 12 cc.; no. 2, 22 cc.; no. 3, 32 cc., no. 4, 42 cc.; and no. 5, 52 cc. When the air current was started a very small quantity of water was drawn out of no. 4 and a rather large quantity out of no. 5. In other words, 42 cc. per 100 gm. of soil was all the water this soil would hold and at the same time permit the passage of a current of air. Moisture determinations at the end of the experiment showed no change in the content of no. 1 and 4; no. 2 and 3 showed slight increases; while no. 5, showed a decided decrease. No curves are plotted for no. 5.

The production of carbon dioxide was remarkably uniform, giving typical curves. There were very slight differences in carbon dioxide formation compared with the wide differences in moisture content. The maximum carbon-

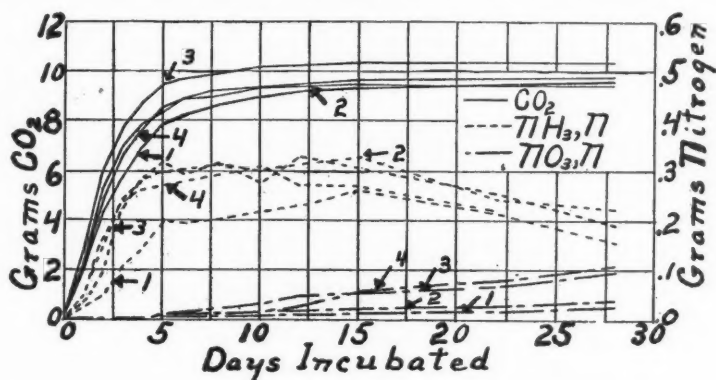


FIG. 3. FORMATION OF CARBON DIOXIDE, AMMONIA AND NITRATES IN EXPERIMENT B

Soil contained 1 per cent cottonseed meal and was aerated continuously. Moisture content: No. 1, 12 cc.; No. 2, 22 cc.; No. 3, 32 cc.; No. 4, 42 cc. per 100 gm. soil.

dioxide production took place during the second 24 hours. By the end of a week approximately 90 per cent of the carbon dioxide evolved during the four weeks the experiment was running had been given off.

The ammonia nitrogen curves for those samples containing more than 12 cc. of water per 100 gm. of soil follow very closely the carbon dioxide curves until nitrification begins. After nitrification became active the ammonia curves fell as the nitrate curves rose. The ammonia curve for the sample containing 12 cc. of water per 100 gm. of soil falls much below the others. This would indicate that the quantity of moisture necessary for favorable ammonia production is higher than for favorable carbon dioxide production.

The nitrate nitrogen when plotted gave practically straight lines. Nitrates did not begin to accumulate until about the fifth day, and for some unknown reason nitrification in all samples was very slow for this soil. The quantities of nitrate nitrogen present increased as the moisture content was raised up to the maximum moisture that the soil would retain.

TABLE 3
Experiment C. Formation of CO₂, ammonia and nitrates in soil containing varying quantities of water; 1 per cent cottonseed meal and 0.5 per cent calcium carbonate added

DAYS	MILLIGRAMS OF CO ₂ AND NITROGEN AS NH ₃ AND NO ₃ PER 1000 GM. OF SOIL														
	11 cc. H ₂ O per 100 gm.					26 cc. H ₂ O per 100 gm.					41 cc. H ₂ O per 100 gm.				
	No. 1			No. 2			No. 3			No. 4			No. 5		
	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.	CO ₂ mgm.	NH ₃ mgm.	NO ₃ mgm.
1	643	26.1	6.8	665	14.7	6.8	1,776	17.1	Trace	1,870	13.0	Trace	2,090	11.4	0
2	940	12.2	3.4	928		Trace	1,650	66.8	0	1,568	51.3	0	1,627	31.0	0
3	776	16.3	3.4	898	13.0	Trace	2,039	163.0	0	1,944	153.2	0	1,827	117.4	0
4	800	13.0	3.0	875	19.2	Trace	1,533	205.4	3.4	1,690	197.2	3.4	1,546	145.1	0
5	695	27.7	4.5	695	27.7	3.0	1,052	244.5	4.5	1,052	238.0	4.5	1,038	200.5	Trace
6	675	44.0	4.5	785	40.7	3.0	815	269.7	7.5	726	267.1	6.8	915	211.1	Trace
7-8	605	57.1	7.5	668	60.3	6.8	636	283.6	16.2	652	224.9	16.2	793	246.0	7.7
9-11	761	78.5	12.2	778	88.0	10.6	787	270.6	38.5	745	260.8	35.0	1,007	214.3	19.4
12-15		83.2	3.4	541	92.2	3.4	568	241.0	32.7	541	234.7	34.0	725	175.8	85.0
16-24		135.0	4.5	720	107.9	3.5	870	252.2	21.4	820	233.2	21.4	860	220.2	13.7
25-39		170.8	6.2	1,056	153.2	6.0	1,050	172.8	210.0	146.4	210.0	16.3	1,221	16.3	420.0

There is some irregularity in the quantity of ammonia recorded from the fifth to the fifteenth day due no doubt to the inability to secure an absolutely representative sample of soil when only the surface soil is taken. So far, no method has been devised for overcoming this objection without at the same time upsetting other experimental conditions.

Experiment C, recorded in table 3 and figure 4, also has to do with the influence of varying the moisture content. One thousand grams of soil containing 1 per cent cottonseed meal and 0.5 per cent calcium carbonate were placed in each of six cylinders. No. 1 and 2 contained sufficient moisture to bring the content up to 11 cc. per 100 gm. of soil. The moisture content of no. 3 and 4, and that of no. 5 and 6 were brought, respectively, to 26 and 41 cc. per 100 gm. of soil. The experiment was continued for 39 days.

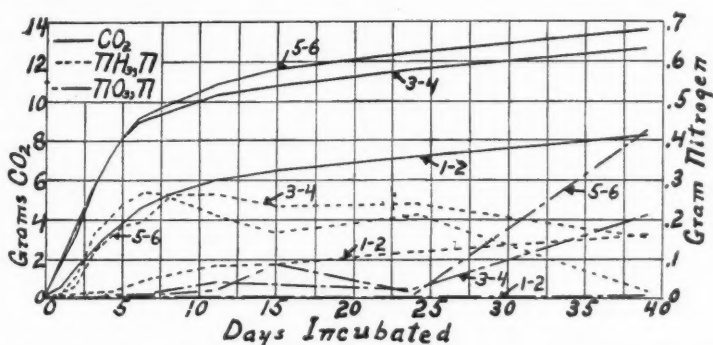


FIG. 4. FORMATION OF CARBON DIOXIDE, AMMONIA AND NITRATE IN EXPERIMENT C

Soil contained 1 per cent cottonseed meal and 0.5 per cent calcium carbonate and was aerated continuously. Moisture content: No. 1 and 2, 11 cc.; No. 3 and 4, 26 cc.; No. 5 and 6, 41 cc. per 100 gm.

Samples 3 to 6 gave the normal carbon dioxide and ammonia curves. Samples 1 and 2, however, evidently did not contain sufficient moisture for maximum bacterial activity. This is evident from the formation of carbon dioxide, ammonia and nitrate. The moisture in this instance is only slightly less than that present in sample 1, experiment B. There is a large difference, however, in the rate of carbon dioxide and ammonia formation. This would indicate that the minimum moisture content for active carbon dioxide and ammonia formation for this soil is near 12 cc. per 100 gm. of soil. For some unknown reason nitrification was depressed somewhere between the fifteenth and twenty-fourth day analyses. Aside from this irregularity the curves are regarded as satisfactory. This depression in nitrification caused a second rise in the ammonia curves. The moisture content of samples 1 and 2 was not sufficient for nitrate accumulation to take place. Apparently the only effect of the calcium carbonate was to increase slightly the total carbon dioxide evolved.

EFFECT OF VARYING AERATION

The following experiments were carried out to ascertain the effect of varying the rate of aeration upon parallel formation of carbon dioxide, ammonia and nitrate in the same soil. In experiment D (table 4 and figure 5) six cylinders of 2000 gm. of soil containing 1 per cent cottonseed meal and 22 cc. of water per 100 gm. of soil were prepared. Through no. 1, 2, and 3, a current of air was drawn continuously. Through no. 4, 5 and 6 the air was drawn $\frac{1}{2}$ hour daily just before the analyses were made. The experiment was continued for 41 days. The results from cylinder 3 were not regarded as satisfactory and are not recorded.

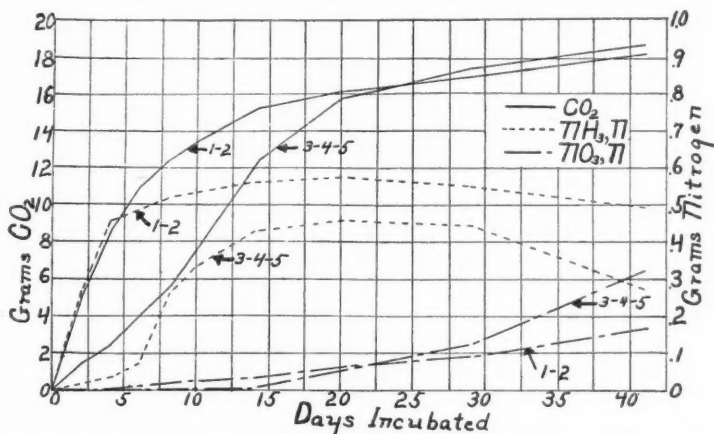


FIG. 5. FORMATION OF CARBON DIOXIDE AMMONIA AND NITRATES IN EXPERIMENT D

Soil contained 1 per cent cottonseed meal and 22 cc. water per 100 gm. No. 1 and 2 aerated continuously, No. 3 to 5 aerated $\frac{1}{2}$ hour daily.

The samples aerated continuously gave the characteristic carbon dioxide and ammonia curves. The carbon-dioxide curve for samples aerated $\frac{1}{2}$ hour daily lagged behind and equalled the normal curve only after 3 weeks. The ammonia curve for these samples was depressed even more markedly than the carbon dioxide curve and failed to reach the normal curve during the course of the experiment. If the carbon dioxide curve were the only measure of bacterial activity available it might be assumed that aerating $\frac{1}{2}$ hour daily failed effectively to remove carbon dioxide. The ammonia determinations, however, were not dependent upon volatilization, and since it was depressed more than the carbon dioxide formation we are justified in assuming that the carbon dioxide curve actually represents carbon-dioxide formation.

The more or less anaerobic conditions existing in the poorly aerated samples for the first two weeks did not exist after that time, else no accumulation of nitrate nitrogen could have taken place. The vigorous oxidation of the easily oxidized organic matter probably utilized all available oxygen. As such

TABLE 5

Experiment E. Formation of CO_2 and ammonia in soil variously aerated; 1 per cent cottonseed meal and 22 per cent water added

DAYS	MILLIGRAMS OF CO_2 AND NITROGEN AS NH_3 PER 1750 GM. OF SOIL							
	Aerated continuously				Aerated $\frac{1}{2}$ hour daily			
	No. 1		No. 2		No. 3		No. 4	
	CO_2	NH_3	CO_2	NH_3	CO_2	NH_3	CO_2	NH_3
	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
2	4,588	77	4,048	80	1,628	10	1,452	10
2	4,796	388	4,356	395	1,276	17	1,012	21
2	2,090	427	1,947	462	1,001	38	913	66
2	1,276	469	1,364	476	1,309	161	847	210
4	1,034	455	1,210	448	2,354	304	1,980	285

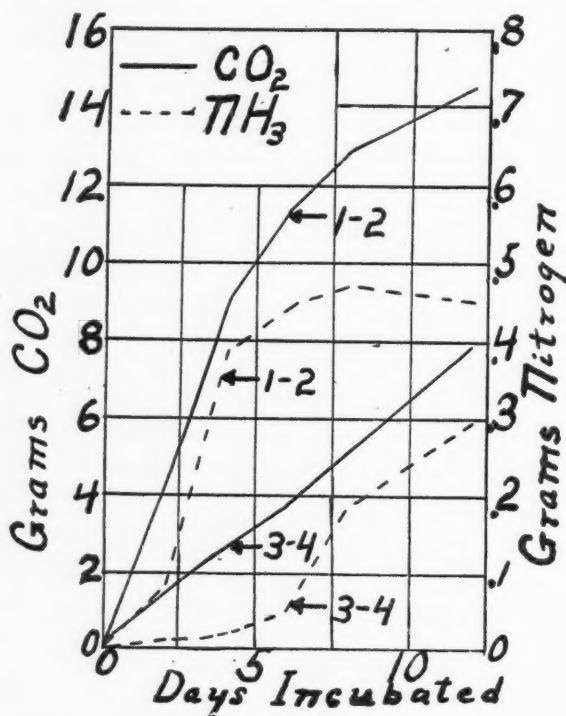


FIG. 6. FORMATION OF CARBON DIOXIDE AND AMMONIA IN EXPERIMENT E

Soil contained 1 per cent cottonseed meal and 22 cc. water per 100 gm. No. 1 and 2 aerated continuously, No. 3 and 4 aerated $\frac{1}{2}$ hour daily.

organic matter rapidly became less a smaller quantity of oxygen was needed for this purpose, and finally reached after two weeks, a point where sufficient oxygen was available for both the oxidation of organic matter and for active nitrification. After nitrification began in the less highly aerated samples, it was much more vigorous than in the better aerated cylinders. This is in accord with results previously published by the writer (1) in which it was shown that the accumulation of nitrate nitrogen took place more rapidly in the bottom of cylinders of soil than in the top, provided aeration was not entirely eliminated by a high moisture content.

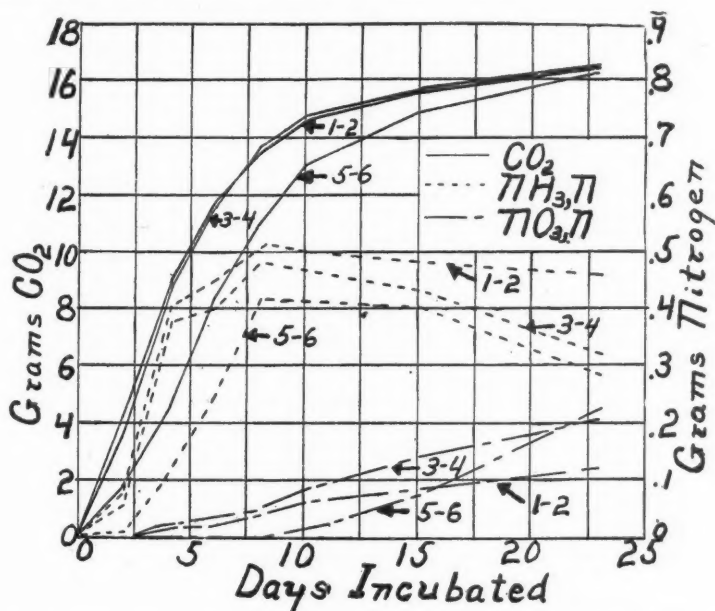


FIG. 7. FORMATION OF CARBON DIOXIDE, AMMONIA AND NITRATES IN EXPERIMENT F

Soil contained 1 per cent cottonseed meal and 21 cc. water per 100 gm. No. 1 and 2 aerated abundantly and continuously. No. 3 and 4 aerated slowly though continuously. No. 5 and 6 aerated 8 a.m. to 6 p.m.

Experiment E is a duplicate of experiment D except that 1750 gm. of soil were used instead of 2000. A comparison of the data secured from this experiment, table 5 and figure 6, with that of experiment D will show that one is practically a duplication of the other. This experiment was continued for only 12 days and the quantities of nitrate nitrogen were so small that they are not recorded.

In experiment F, recorded in table 6 and figure 7, 2000 gm. of soil containing 1 per cent cottonseed meal and 21 cc. of water per 100 gm. of soil, were

TABLE 6
Experiment F. Formation of CO₂, ammonia and nitrates in soil variously aerated; 1 per cent cottonseed meal and 21 per cent water added

DAYS	MILLIGRAMS OF CO ₂ AND NITROGEN AS NH ₃ AND NO ₃ PER 2000 GM. OF SOIL											
	Aerated strongly, continuously						Aerated slow, continuously					
	No. 1			No. 2			No. 3			No. 4		
	CO ₂	NH ₃	NO ₃	CO ₂	NH ₃	NO ₃	CO ₂	NH ₃	NO ₃	CO ₂	NH ₃	NO ₃
2	4,290	80	0	4,048	84	Trace	3,850	56	Trace	1,826	10	0
2	5,160	404	13	4,446	392	12	5,160	372	17	2,870	102	0
2	2,982	456	22	2,640	444	22	3,128	428	30	3,788	248	0
2	1,656	504	38	1,824	516	43	1,954	476	43	2,692	424	0
2	1,138	504	67	1,088	496	59	1,016	460	81	1,948	428	11
5	1,012	472	81	914	492	85	1,100	424	141	1,830	404	72
8	878	476	122	980	444	122	890	346	208	1,414	286	216

Aerated 8 a.m. to 6 p.m.

mgm.

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placed in each of 6 cylinders. Through no. 1 and 2 a strong current of air was drawn all the time. Through no. 3 and 4, a continuous current of air was drawn but the volume was reduced as low as was possible to still be kept passing. The former was at least ten times as strong as the latter. Through no. 5 and 6 the current of air was drawn from 8 a.m. to 6 p.m., being run $\frac{1}{2}$ hour before analysis. The experiment was continued for 23 days.

The carbon dioxide and ammonia curves for samples 1 to 4 are again typical. Both the carbon dioxide and ammonia curves for no. 5 and 6 lag somewhat behind, indicating that aeration only during the work day was not sufficient to maintain optimum conditions for aerobic bacterial activity. Again, nitrate accumulation in the less highly aerated cylinders was more rapid when once established than in the other cylinders. The accumulation of nitrate nitrogen in this experiment is in agreement with experiment E.

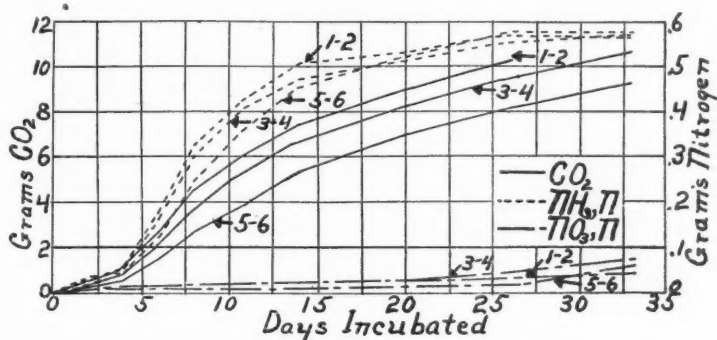


FIG. 8. FORMATION OF CARBON DIOXIDE, AMMONIA AND NITRATES IN EXPERIMENT G

Soil contained 1 per cent dried blood and 22 cc. water per 100 gm. No. 1 and 2 aerated continuously. No. 3 and 4 aerated 8 a.m. to 6 p.m. No. 5 and 6 aerated 1 hour daily.

One thousand grams of soil containing 1 per cent dried blood and 22 cc. of water per 100 gm. of soil were used in experiment C. Through no. 1 and 2 the current of air was kept continuous, through no. 3 and 4 from 8 a.m. to 6 p.m., and through no. 5 and 6 one hour daily just before being analysed. The results are recorded in table 7 and figure 8.

The difference in the character of the organic material added modifies decidedly the character of the curves for carbon dioxide and ammonia. The nitrogen content of this dried blood was approximately twice that of the cottonseed meal. The relative position of the carbon dioxide and ammonia curves is reversed, the latter being higher than the former. This is apparently due not to an increased ammonia formation but to a depressed carbon dioxide formation.

During the first four days under normal conditions where cottonseed meal was added, approximately 50 per cent of the carbon dioxide and ammonia formed

during the course of the experiments, was recovered. From dried blood, only small quantities were recovered at the end of 4 days. After the fourth day analyses the curves for ammonia were very similar to those in previous experiments. The formation of carbon dioxide, however, was still comparatively slow, the most rapid evolution taking place between the sixth and eighth day analyses. After this the curves tend gradually toward straight lines, but with a more decided tendency upward than shown by carbon dioxide curves for the latter stages of the experiments where cottonseed meal was added. These various facts would indicate that the organic carbon of dried blood is not nearly so easily oxidized by soil organisms as is the carbon of cottonseed meal. Neither was the nitrogen of dried blood liberated as ammonia in this experiment as rapidly or as completely as was that of cottonseed meal. The experimental data available are not sufficient for us to conclude that this would hold true for other soils, or for other samples of dried blood and cottonseed meal in the same soil.

The effect of variation in aeration is evident both on the carbon dioxide and ammonia curves. The depressions due to decreased aeration are not, however, of the same nature or degree as in those experiments where cottonseed meal was added to the soil.

The nitrate nitrogen accumulated very slowly in all samples, but toward the end of the experiment nitrification appeared to be inversely proportional to aeration.

DISCUSSION AND SUMMARY

In studying the several sets of data, and curves constructed therefrom, several rather striking facts are to be noted. In the first place there is a remarkable similarity and agreement between the several carbon dioxide and ammonia curves when constructed from data secured under anything like similar conditions. If conditions are favorable for bacterial activity and cottonseed meal is added, there is at first a very rapid formation of carbon dioxide and ammonia, the maximum being reached during the second 24 hours. After this the formation of both carbon dioxide and ammonia decreased rapidly, the curves soon tending toward straight lines. When dried blood was added to the soil the curves for both carbon dioxide and ammonia were different. Formation during the first 4 days was very slow, the maximum being reached between the sixth and eighth day analyses. The formation of carbon dioxide from dried blood was never so rapid as from cottonseed meal, but was apparently distributed over a longer period of time.

Insufficient moisture retards both carbon dioxide and ammonia formation, the latter much more markedly. The minimum moisture for active carbon-dioxide production is lower than for active ammonia production. For the soil used in these experiments 12 cc. of water per 100 gm. soil was near the minimum for vigorous carbon-dioxide production, and increasing the moisture

beyond this point had little effect upon the formation of carbon dioxide. A moisture content below this results in a lowered carbon-dioxide production. The moisture necessary for optimum ammonia formation is higher than that for carbon dioxide.

Insufficient aeration will also cause a depression or marked delay in carbon dioxide and ammonia production. The data here recorded are insufficient as a basis for a statement as to the oxygen necessarily available for maximum aerobic biological activity. In no instance where the current of air was not continuous was the production of carbon dioxide and ammonia equally as rapid as where it was. In the case of carbon dioxide it appears to be simply a delayed production, the total quantity soon reaching that produced where aeration was abundant. The total ammonia produced under limited aeration did not, in most instances, reach the production where aeration was abundant. So long as the current of air was continuous, increasing the volume apparently had no effect.

Where moisture and aeration are both favorable the ammonia production follows very closely the evolution of carbon dioxide. Unfavorable conditions, however, have a more detrimental effect upon the formation of ammonia than upon the formation of carbon dioxide.

Carbon dioxide production from dried blood is not nearly so rapid as it is from cottonseed meal. Neither is the curve similar. There is a relatively greater ammonia production per unit of carbon dioxide produced from dried blood than from cottonseed meal. This is probably due to the higher nitrogen content. Per unit of nitrogen, that contained in cottonseed meal is liberated much more rapidly than that in dried blood. This may possibly be due to the particular sample of dried blood though it has usually been the writer's experience that when equal quantities of nitrogen are added to soil in the two forms that in cottonseed meal is ammonified more rapidly. The low carbon dioxide production would seem to indicate that the rapidly oxidizable carbon was perhaps so limited that sufficient energy was not available for breaking up the nitrogen combinations. If ammonia is simply a by-product, as sometimes regarded, and sufficient quantities of easily oxidized carbon were present in the dried blood, then it would seem we should get proportionately higher ammonia liberated where the higher per cent of nitrogen was present.

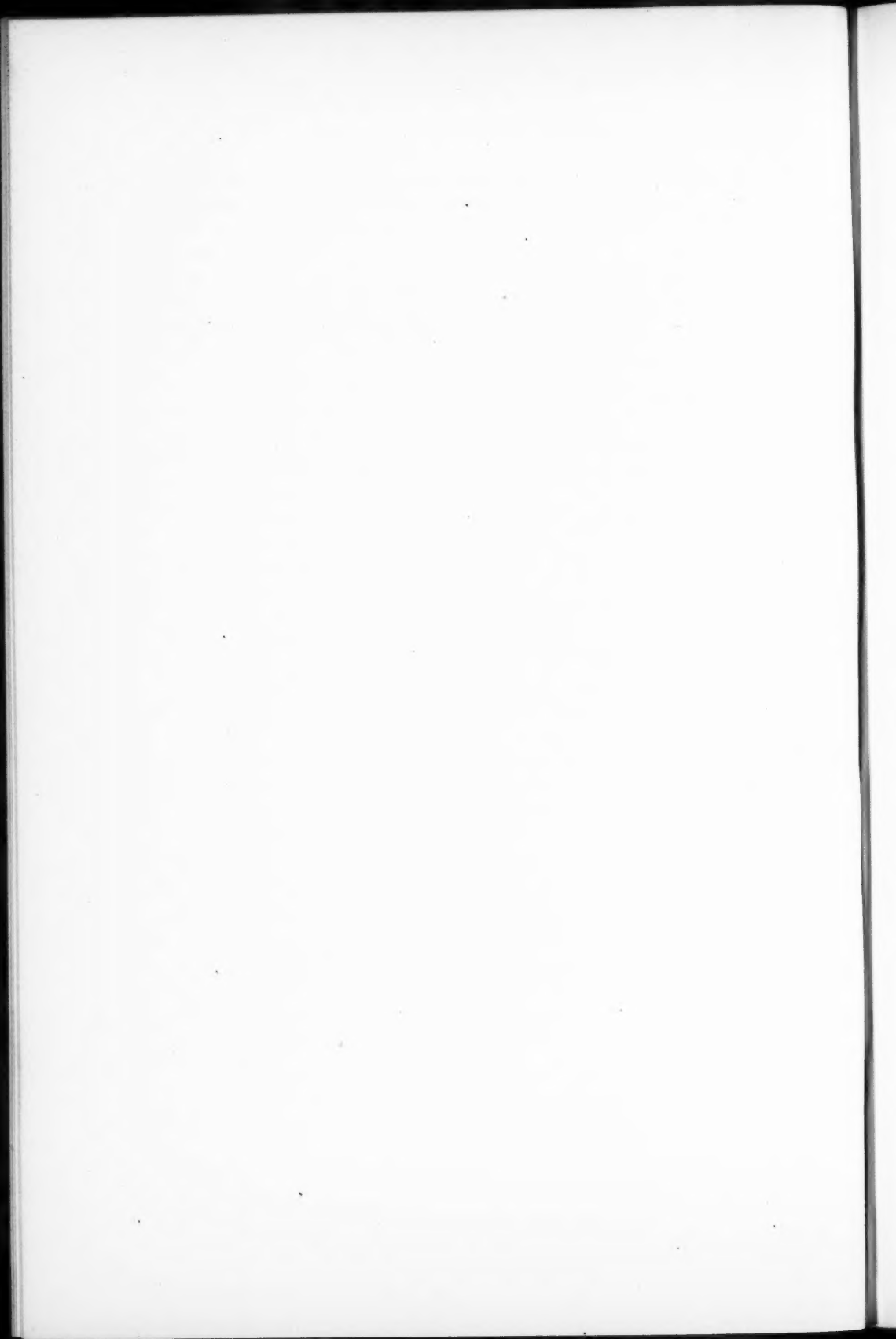
Nitrate production in all experiments was for some unknown reason exceptionally low for this particular soil. As a rule there was no accumulation during the first few days. In fact the small quantity of nitrate nitrogen initially present (left out of consideration in records) usually disappeared completely before the first analysis. Where aeration was insufficient the beginning of accumulation was delayed still more.

Where the moisture content was varied, nitrate accumulation was directly proportional to moisture content, the maximum not being reached until the maximum moisture that would be retained was reached. Where aeration

was varied insufficient aeration retarded the initial accumulation, but after nitrification became active in all samples the accumulation was inversely proportional to aeration.

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- (2) POTTER, R. S., AND SNYDER, R. S. 1916. Carbon-dioxide production in soils and carbon and nitrogen changes in soils variously treated. Iowa Agr. Exp. Sta. Res. Bul. 39, p. 253-309.



THE MOVEMENT OF MOISTURE IN SOIL BY CAPILLARITY

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The individuals of a mass of spherical soil particles of uniform size will come in contact at a maximum of twelve points, and if moisture be present it will adhere as a thin film about the surface with ring-shaped water wedges about the points of contact. From a consideration of the geometrical configuration, it may be seen that changes in curvature of the air-water surface depend upon changes in the moisture content. It is well known that dry soil in contact with moist soil will absorb a part of the moisture, and the above explanation is generally accepted by soil workers.

For the case of horizontal capillary movement, hydrostatic pressure does not enter and the gradient of the curvature pressure is a measure of the kinematical force acting on the water which is free to move. The thin hygroscopic film is held (1) to be in a solid phase or in loose chemical combination and in this discussion may perhaps be regarded as a part of the solid soil particle. Where the pore space is completely filled with water the air-water surface disappears and movement depends upon the hydrostatic pressure gradient. Slichter (2) has observed that the hydrostatic pressure in this case satisfies Laplace's equation and he has made some extended theoretical mathematical calculations for the flow of under-ground water under pressure, which have found fair experimental verification. The only assumption underlying his theory is that the velocity is proportional to the pressure gradient, and by substituting for the velocity components in the equation of continuity for incompressible fluids these simple functions of the pressure, he arrives immediately at Laplace's equation.

The essential distinction between the case considered by Slichter and the case of capillary flow would seem to be that the density (i.e., the mass of moisture per unit volume in the soil) is dependent upon the space coordinates and also upon the time; also that the pressure is a function of the density. It is to be noted that the relative motion of rigid soil particle and moisture surrounding it is somewhat analogous to the case of the motion of a particle falling through a viscous fluid, and, on the basis of Stokes' law for this case, the assumption is made that the velocity is proportional to the pressure gradient, but the pressure is proportional to the curvature and the curvature is a determinate function of the density for the idealized case under consideration. The air-water surface configuration in a typical soil is, however,

only approximately similar to the ideal case and therefore a rigorous determination of this function has not been attempted. By reference to figure 1 it will be observed that the water wedge is enclosed by the surface of revolution generated by revolving arcs ab , bc , and ca about the line of centers of the spheres. The radii of curvature of the principal sections are oppositely directed and vanish together, but the one will approach the radius of the soil grain as a maximum while the other becomes infinite. The following relation has been assumed:

$$-r_1 = \frac{ar_2}{br_2 + c} \quad (1)$$

where r_1 and r_2 are the radii of curvature and a , b , and c are undetermined constants.

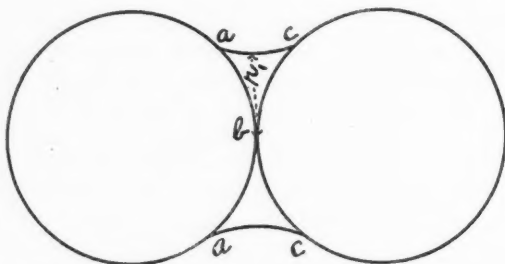


FIG. 1. OUTLINE OF WATER WEDGE BETWEEN TWO SOIL PARTICLES

The pressure under a curved surface may be expressed:

$$p = 2T(1/r_1 - 1/r_2) \quad (2)$$

where T is written for the surface tension and p for the pressure. The volume of the water wedge, which is proportional to the density, is also a function of r_1 and we have assumed that it is proportional to r_1^3 ,

$$\rho = k_1 r_1^3 \quad (3)$$

where ρ is the density, k_1 an undetermined constant. From equations (1), (2), and (3), we may arrive at once at the relation:

$$dp/dx = k_2/\rho^3 d\rho/dx \quad (4)$$

k_2 being a constant involving a , b , c , T and k_1 .

Stokes' law may be expressed:

$$v = k_3/\eta dp/dx \quad (5)$$

where k_3 involves the radius of the soil particle and η is the coefficient of viscosity of the liquid ($\frac{dp}{dx}$ substituted for the gravitational acceleration constant).

The equation of continuity for one-dimensional flow may be written:

$$\frac{\partial \rho}{\partial t} = - \frac{\partial}{\partial x} (\rho v) \quad (6)$$

and a combination of (4), (5), and (6) gives,

$$\frac{\partial \rho}{\partial t} = - \frac{k_s}{\eta} \frac{\partial}{\partial x} \left(\frac{\partial \rho}{\partial x} \cdot \frac{1}{\rho^{\frac{1}{3}}} \right) \quad (7)$$

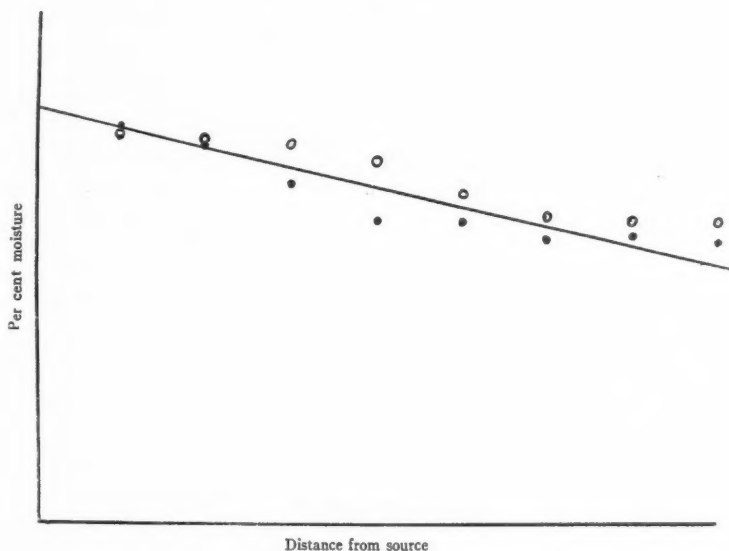


FIG. 2. DIAGRAM ILLUSTRATING WIDTSTOE'S DATA

Small circles represent data from irrigated farms, black dots data from dry farms.

as the differential equation for capillary motion. For the case of a steady state, this becomes,

$$\rho \frac{\partial^2 \rho}{\partial x^2} = \frac{1}{3} \left(\frac{\partial \rho}{\partial x} \right)^2 \quad (8)$$

and the solution

$$\rho = (Ax + B)^{3/2} \quad (9)$$

where A and B are integration constants.

A number of experimental cases have been considered. Widtsoe (3) has made extended investigations in soil moisture and finds the winter precipitation distributed in early spring as illustrated in figure 2. The curve is plotted from equation (9) with assumed values for A and B . The small circles rep-

resent Widtsoe's data from irrigated farms and the black dots data from dry farms.

In the laboratory at the Utah Experiment Station several preliminary observations have been made as to the moisture distribution at the steady state. The moisture was allowed to penetrate by capillarity into horizontal tubes of about 4 cm. diameter containing fine sand. The moisture was

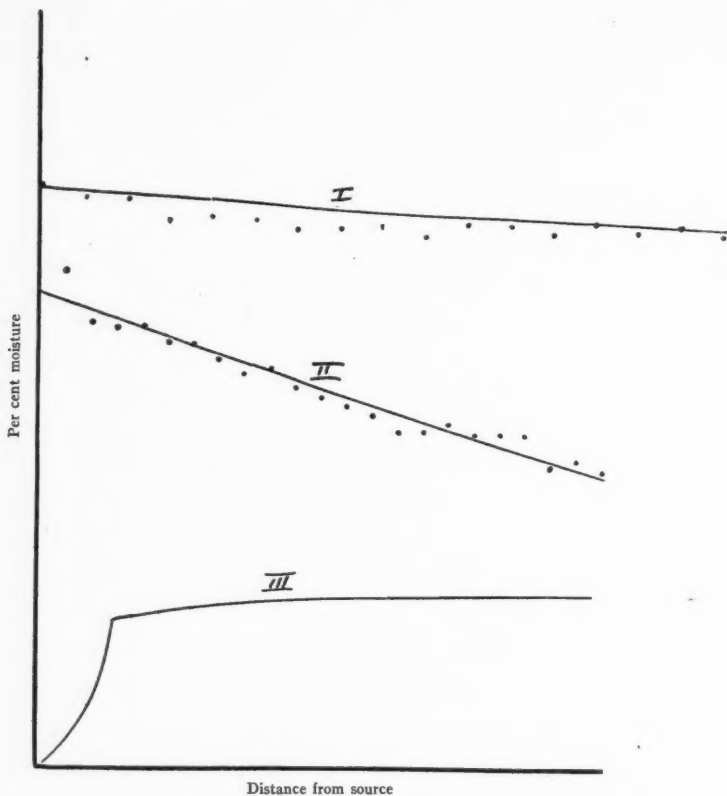


FIG. 3. CURVES SHOWING LABORATORY DATA AND MOMENT OF MOISTURE AS IT VARIES WITH THE TIME

evaporated from the remote end. The tubes, about 6 feet in length, were mounted in such a way as to rotate about an axis perpendicular to the tube and a record of the changing moment due to the moisture as it crept forward was kept as a guide to the degree to which a steady state was approached. In figure 3, curve III, is plotted the moment of the moisture as it varied with the time, the ordinate in this case being the moment and the abscissa the time.

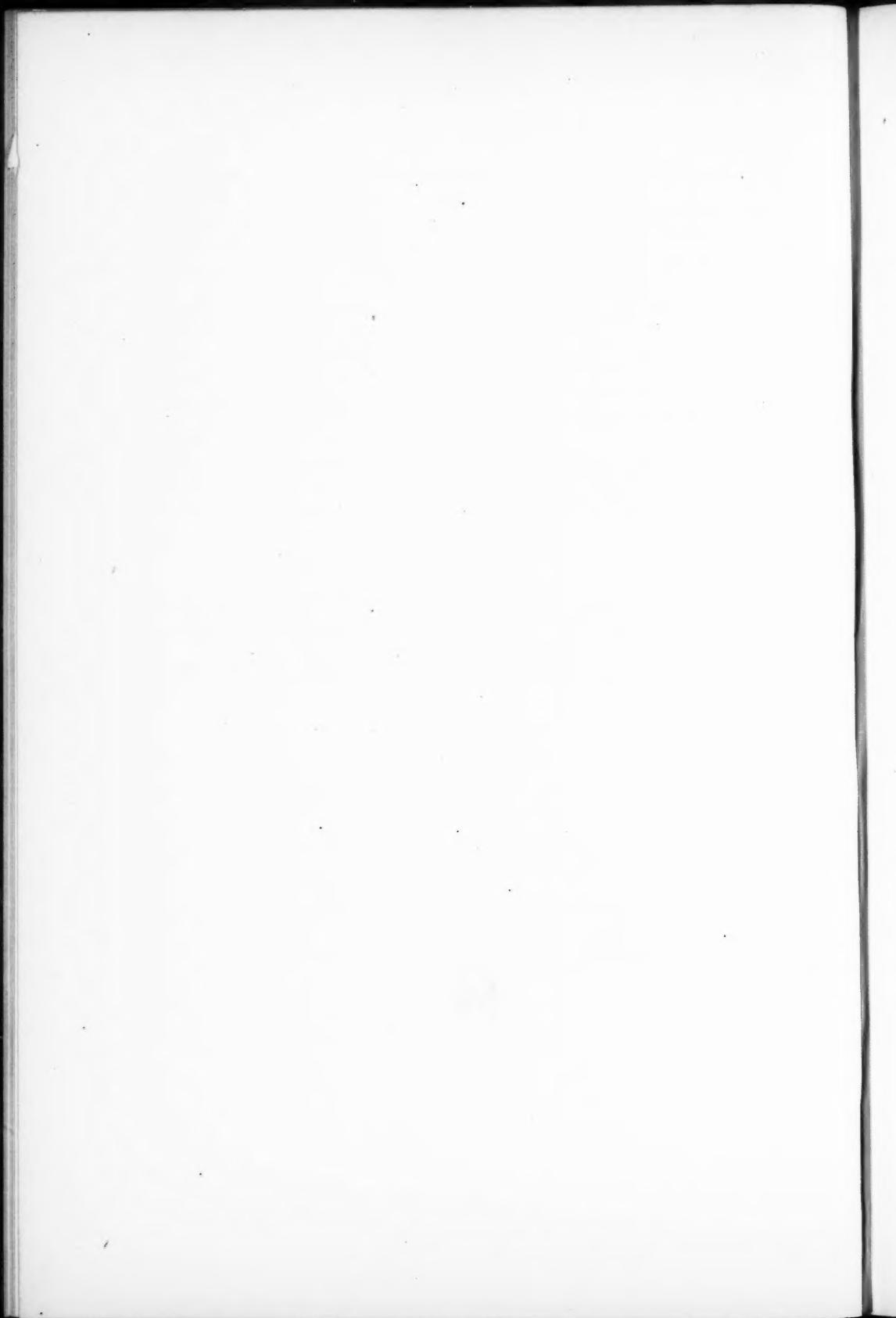
Curve II of figure 3 was calculated from equation (9) with assumed values for A and B . The dots represent the mean of a series of three experimental determinations. In curve I are shown the results of a single observation made with a different soil and with a slightly different method, the curve again in this case being calculated and the dots representing experimental values.

The assumptions which have been made in the theoretical considerations above may affect the magnitude of the exponent in equation (9) but the experimental data would seem to indicate that equation (9) is not far from correct. As will be noted, the experimental errors are rather large, owing to the fact that slight irregularities in the manner of packing the soil and other attendant experimental difficulties tend to modify results obtained.

In conclusion, I wish to acknowledge the able assistance rendered by Mr. Scott Ewing in obtaining the experimental results in the laboratory and the coöperative encouragement of Dr. F. L. West, the head of the Physics Department.

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CAPILLARY MOISTURE-HOLDING CAPACITY

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It has been pointed out that the moisture-holding capacity as defined by Hilgard (7) does not correspond with the amount actually found in the field after irrigation or heavy rain. Israelsen (8, p. 22) gives ratios of the amount found by a method similar to the Hilgard method to the amount found in the field after irrigation ranging from 1.32 to 2.30; and Alway (1, p. 410) gives ratios of 1.5 to 2.

Briggs (4, 5) explained the movement of capillary water on the basis of well known surface tension phenomena and his view seems to be quite generally accepted. Widtsoe (10) discusses soil moisture from the standpoint of film thickness, indicating several stages in the mobility of water over the soil grains. Bouyoucos (3) has given evidence that the hygroscopic film may be in a solid phase and it is maintained that there may be a somewhat unstable chemical combination of a part of this moisture with the soil. It is believed, however, that water in excess of that designated by Widtsoe as the lenticapillarity point may respond to the capillary forces. In fact, from the mechanical point of view, water of hydration and "solid" water alone may be excluded, but soil water in such condition is only a small part of the total quantity present in ordinary moist soils.

On the basis of these facts, we are confronted with the inevitable deduction that a state of equilibrium in soil moisture, exclusive of the hygroscopic moisture, would demand a curvature gradient, and consequently a moisture gradient, of such a magnitude as to supply a force equal to the force due to gravity, assuming that adhesive forces are negligible beyond the lenticapillarity point. There is abundant evidence that capillary movement is comparatively slow and static equilibrium is the exception rather than the rule. It is therefore to be expected that a decided difference may exist between the moisture capacity of a soil as defined by Hilgard and the average amount found in the region of root activity immediately after heavy irrigation or at any subsequent time, although an accidental agreement may be found at some stage during the process of adjustment to equilibrium. Alway (1, p. 415) reports the ratio of the water content to the hygroscopic coefficient in the first and second 3-inch sections of two series of soil tubes, the first of which were allowed to stand five days and the second from 66 to 110 days after "irrigation," protected from surface evaporation. His results are

quoted in table 1. It would no doubt be admitted that final equilibrium had not been attained although with a low moisture content the movement may be very slow.

In a somewhat similar experiment, King (9) found that the process of readjustment continued in some cases for $2\frac{1}{2}$ years, but in every case the final moisture per cent was found to increase with increasing depth. In

TABLE 1

Extent to which equilibrium had been attained by the different soils at the end of 5 days, as shown by comparing the ratios of water content to hygroscopic coefficient in the first and second 3-inch sections in the present experiment (I) with those found in an earlier one (II) in which the exposure had been much longer

SOIL	HYGRO-SCOPIC CO-EFFICIENT	EXPERIMENT NO.	INITIAL RATIO	AMOUNT OF WATER ADDED	TIME OF EXPOSURE	RATIO AT END OF EXPERIMENT		FALL IN RATIO AFTER FIFTH DAY	
						1 to 3 in. section	4 to 6 in. section	1 to 3 in. section	4 to 6 in. section
				<i>inches</i>	<i>days</i>				
A	13.3	I	1.0	1.00	5	1.9	1.7	0.0	0.0
		II	1.0	2.11	110	2.0	1.8		
B	12.9	I	1.0	1.00	5	1.8	1.6	0.0	0.0
		II	1.0	2.12	69	1.9	1.8		
C	10.5	I	1.1	1.00	5	2.2	1.9	0.1	0.0
		II	1.1	1.21	100	2.1	1.9		
D	10.2	I	1.0	1.00	5	2.4	1.9	0.2	0.0
		II	1.3	0.90	110	2.2	2.0		
E	10.1	I	1.0	1.00	5	2.1	2.0	0.2	0.2
		II	1.0	1.42	100	1.9	1.8		
G	8.2	I	1.0	1.00	5	2.2	2.0	0.2	0.0
		II	1.0	1.58	106	2.0	2.0		
H	7.6	I	1.0	1.00	5	2.4	2.2	0.1	0.1
		II	1.2	1.28	102	2.3	2.1		
I	7.1	I	1.1	1.00	5	2.3	1.9	0.2	0.0
		II	1.2	0.60	102	2.1	1.9		
J	5.6	I	1.0	1.00	5	2.6	2.2	0.5	0.3
		II	1.0	0.89	70	2.1	1.9		
K	3.4	I	1.1	1.00	5	3.7	3.0	1.5	1.1
		II	1.3	0.33	100	2.2	1.9		
L	3.4	I	1.0	1.00	5	2.9	2.7	1.2	1.1
		II	1.3	0.27	68	1.7	1.6		
M	3.3	I	1.1	1.00	5	4.1	3.0	1.7	1.0
		II	1.3	0.35	100	1.4	2.0		

figure 1 a plot of results given by him is shown for soils of varying texture from sands to clay loams. The finer soils represented by the higher curves were allowed to stand 60 days whereas dripping continued with the sands for nearly $2\frac{1}{2}$ years.

Table 2 is also quoted from the work of Alway (2, p. 35). At a superficial glance, the data here presented would seem to indicate that an equilibrium condition with uniform moisture distribution may have been attained in

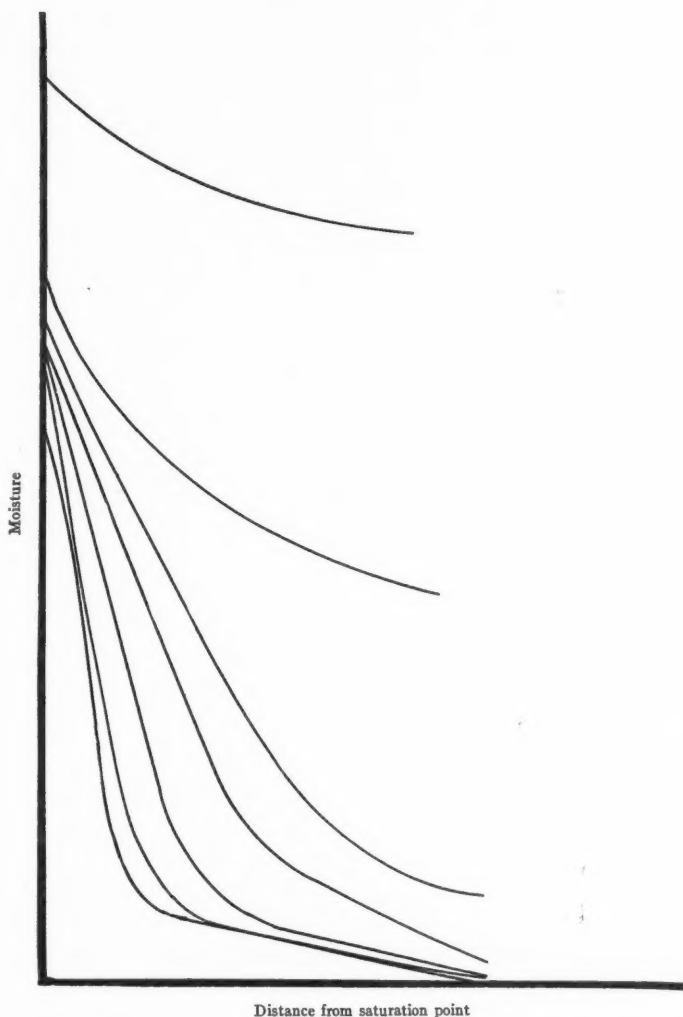


FIG. 1. CURVES REPRESENTING RELATION OF MOISTURE CONTENT TO DISTANCE FROM SATURATION POINT IN DIFFERENT SOILS

the case of soil tubes IV, V, VI, and VII, which had remained standing for 96, 104, 109 and 126 days, respectively, showing but slight variation with the time at every section to the total depth of 30 inches after the 96-day period. The process of readjustment to equilibrium being a very slow process, however, it may be that the actual change during this interval was of the order of

TABLE 2

Ratio of water content to hygroscopic coefficient in soil J, entirely protected from evaporation, but in capillary connection with the earth's soil mass; to the cylinders, each filled with approximately 50 pounds of air-dried soil, there was added 15 pounds of water, after which they were left 31 to 126 days

DEPTH OF SECTION	CYLINDER NUMBER								
	I (31 days)	II (44 days)	III (54 days)	IV (96 days)	V (104 days)	VI (109 days)	VII (126 days)	IV-VII (average 109 days)	IX* Sand at bottom
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1	3.1	3.3	3.1	2.5	3.0	2.6	2.6	2.6	3.4
2	3.1	3.2	3.0	2.4	2.8	2.6	2.5	2.6	3.2
3	3.1	3.2	3.1	2.3	2.7	2.5	2.5	2.5	3.2
4	3.2	3.2	3.1	2.4	2.6	2.5	2.5	2.5	3.2
5	3.3	3.2	3.1	2.4	2.6	2.5	2.5	2.5	3.1
6	3.2		3.1	2.4	2.6	2.6	2.4	2.5	3.2
7	3.2	3.2	3.1	2.4	2.6	2.6	2.4	2.5	3.3
8	3.3	3.3	3.2	2.4	2.5	2.5	2.4	2.5	3.3
9	3.4	3.4	3.3	2.4	2.6	2.4	2.4	2.5	3.4
10	3.3	3.4	3.3	2.5*	2.6	2.4	2.4	2.5	3.4
11	3.2	3.5	3.4	2.4	2.6	2.5	2.3	2.4	3.4
12	3.5	3.4	3.3	2.4	2.6	2.5	2.5	2.5	3.4
13	3.6	3.4		2.4	2.6	2.5	2.4	2.5	3.5
14	3.6	3.5	3.4	2.4	2.6	2.4	2.4	2.5	3.5
15	3.7	3.6	3.4	2.4	2.5	2.4	2.5	2.5	3.6
16	3.6	3.4	3.5	2.3	2.5	2.4	2.6	2.4	3.6
17	3.7	3.6	3.5	2.3	2.5	2.4	2.5	2.4	3.7
18	3.7	3.9	3.5	2.3	2.6	2.4	2.5	2.4	3.7
19	3.7	3.7	3.5	2.3	2.6	2.4	2.5	2.4	3.8
20	3.7	3.7	3.6	2.4	2.6	2.4	2.5	2.5	3.8
21	3.8	3.8	3.7	2.3	2.5	2.3	2.5	2.4	3.9
22	4.0	4.1	3.8	2.3	2.6	2.4	2.5	2.4	3.9
23	4.2	3.9	3.8	2.3	2.5	2.4	2.4	2.4	4.0
24	4.2	3.9	3.8	2.3	2.5	2.5	2.5	2.4	4.1
25	4.2	3.9	4.1	2.3	2.5	2.5	2.5	2.4	4.2
26	4.4	4.3	4.2	2.3	2.5	2.5	2.5	2.4	4.3
27	4.5	4.5	4.2	2.3	2.5	2.5	2.5	2.4	4.3
28	4.5	4.3	4.2	2.5	2.4	2.5	2.4	2.5	4.6
29	4.6	4.3	4.5	2.5	2.5	2.5	2.4	2.5	
30	4.8	4.3	4.6	2.5	2.5	2.5	2.5	2.5	
Average....	3.7	3.7	3.6	2.4	2.6	2.5	2.5	2.5	3.6

* Column 9 is the mean for four cylinders similar in every way except that connection is made to soil mass through sand and gravel.

magnitude of the probable error of the determinations. It will be noticed that in soil columns I, II and III, which were left to stand 31, 44 and 54 days, respectively, all of which show a decided increase in moisture content with increasing depth, there is very little change in a period of 23 days. The

seven tubes were treated the same way except that I, II and III were taken from an earlier experiment, and since the condition of the natural subsoil into which these tubes drained is not specified, it seems probable that the subsoil may have changed in moisture content, which would readily account for the difference in moisture content in the two series. A moist soil or a gravel or sand at the bottom of the tubes might operate as an effective seal against the downward flow of water by capillarity. The summarized data from four soil tubes which were treated in every way similar to the seven mentioned above, except that they were connected to the subsoil through sand and gravel at the bottom (2, p. 36) have been added as a final column to table 2, and it will be noted that the distribution at the end of a period of 126 days and the average moisture content are almost exactly the same as in tubes I, II, and III, with a decided increase in moisture content with the depth. Had tubes I, II, and III been allowed to stand 126 days, there is no indication that the moisture distribution and the moisture content would have been the same as in tube VII (which stood 126 days) unless we grant that the time interval from the 54th to the 96th day has some singular significance, which, however, is improbable.

Widtsoe (10) defines field moisture capacity as "the percentage of moisture held in field soils to a depth of 8 to 10 feet, when the top foot is saturated," the implied assumption being that equilibrium distribution has been reached. In such distribution, however, the moisture gradient is reversed, showing a decrease in moisture with increasing depth, and, owing to the great depth of the Greenville soil, a state approximating a *steady*, though not an *equilibrium*, state may perhaps have been attained, whereby the dry deep soil carried the moisture away nearly as fast as it would penetrate from a moist surface, although an observation over longer periods of time would perhaps have shown a slow accumulation at all points below the saturation plane.

It is well known that under specified boundary conditions in such phenomena as the flow of heat, a *steady* state is frequently attained with a finite temperature gradient, but such gradient is dependent upon the nature of the boundary conditions. It is possible that a deep dry soil below the tenth foot would maintain a fairly constant moisture content at this depth for a limited time, but as the moisture front advanced into the soil the distance from the saturated surface to the dry boundary would necessarily increase, accompanied by a corresponding change in the distribution. Widtsoe claims that the condition specified is not far from the optimum for the Greenville soil and it would seem that a rational basis is thus afforded for a definition of field moisture capacity. However, in addition to specifying the moisture condition at the surface, the depth of the dry-moist boundary should be specified. The proper depth to specify may, however, vary with the type of soil.

The experimental determination of a soil constant as thus defined would be difficult and if adopted it is apparent that a correlation with some other

more readily determined soil constant is desirable. Briggs (6) gives the following equations:

$$c = 2.9w + 21$$

$$c = 1.57e + 21$$

$$c = 4.26h + 21$$

where c is written for the moisture capacity as defined by Hilgard, w for wilting coefficient, e for moisture equivalent, and h for hygroscopic coefficient. It is to be expected that similar relations would hold for a moisture capacity as above or equivalently defined. It is evident, however, that the ratio of c in the above equations to any of the other constants, w , e , or h , is not independent of the character of the soil and it is therefore not surprising that Israelsen (8, p. 23) should get values for the ratio e/c' ranging from 1 to 1.72, and that Alway (1, p. 415) should get values ranging from 1.7 to 4.1 for the ratio c'/h , c' in this case being the moisture content after irrigation. Briggs' equations are admittedly empirical, but the constants he refers to have been defined without ambiguity and the equations may no doubt be applied with fair accuracy to any type of soil. As stated, similar functions may be determined with the field-moisture capacity, however it may be defined; but it cannot be too strongly emphasized, in the light of the foregoing, that the dynamic character of typical soil-moisture phenomena cannot be overlooked in the attempt to define such a soil constant, and in order to make positive progress from a scientific as well as practical point of view, it would seem that fundamental concepts of this character should be carefully considered.

A laboratory study of the dynamic phases of soil moisture is under way at the Utah Agricultural Experiment Station and it is hoped that some information may be made available which will help to rationalize studies in this field.

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